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A paper presented at the 182d Meeting of the American Institute of Electrical Engineers, New York, December 18, 1903.
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GAS POWER FOR CENTRAL STATIONS.

The Advantages of Operating Electric Stations in Connection with Gas Works.

BY J. R. BIBBINS.

At the present time two competitors of the reciprocating steam-engine—the steam-turbine and the gas-engine—are attracting wide attention. Engineers, particularly, are interested. Heretofore the interest taken in gas-engine plants seems to have been confined chiefly to those operating in foreign countries, but as there are a number of successful installations of this kind in the United States, it may be of interest to present a few facts about their operation. It is intended in the following pages to offer testimony upon four contentions, viz.:

A. That present gas-power machinery is suitable for central-station service.

B. That a well-equipped gas-power electric-plant can operate with far better economy than a steam-plant under similar conditions.

C. That its operation is much simpler and requires less running expense for the same results.

D. That gas works, laboring under low load or output-factor, can profitably install a gas-power electric generating station, and become its own largest customer, selling both gas and electricity at competitive rates.

The basis of this paper consists of data collected from various electric-light and power-plants in the United States using gas-engines as their principal motive power. A number of these plants being operated in connection with illuminating-gas works, it has been possible to observe the somewhat unique position of

the gas-engine station as a direct though affiliated competitor of the gas works.

TABLE I.—GAS-POWER PLANT EQUIPMENT.

Plant No.	Engines.					Generators.				
	Rated Capacity Full Load, b.h.p.	No.	b.h.p.	Transmission. Character.	Transmission. Efficiency.	Incandescent Power.	Railway.	Arc.	Total kw. Generating capacity.	* b.h.p. Gen. / b.h.p. Eng.
1	685	3	125–280	Belt.	82.5	1-phase.	550 V. D.C.	..	370	.845 (a)
2	170	2	85	"	80	....	..	230 lts.	112	1.00 (b)
3	110	2	55–	Jack-shaft	75	2-phase.	..	..	75	1.2
4	90	2	35–55	Belt.	80	1- "	..	..	40	0 93
5	320	4	55–125	Jack-shaft	75	3- "	..	60 lts.	232	1.18 (c)
6	360	4	55–125	"	75	2- "	..	..	215	1.14
7	305	3	55–125	Belt.	82.5	1- "	..	..	260	1.38
8	280	1	280	"	80	1- "	..	50 lts.	152	0.91
9	140	2	55–85	"	...	1- "	..	..	100	0.96
10	85	1	85	"	80	1- "	..	..	60	1.17
11	803	6	125–210	"	82.5	1- "	..	200 lts.	476	0.97 (d)
12	255	(x) 3	85	'	80	2- "		..	116	0.78 (e)
13	375	3	125	Direct-connected	85	2-.	..	..	225	0.94 (f)
14	500	4	125	"	85	2-.	..	..	300	0.96 (f)
15	840	3	280	"	85	2-.	..	..	450	0.85 (f)

(*) e.h.p. at engine shaft.
(a) Largely railway load—running 15–18 hr. per day.
(b) Exclusively arc.
(c) Monocyclic system—runs 24 hr. per day.
(d) Plants operate 24 hr. per day—Natural-gas
(e) Natural-gas.
(f) Operates in parallel—Natural-gas.
(x) 8-h.p. engine belted to air compressor and pump.
(ϕ) Phase.

Equipment.—Table 1 presents the most important data upon the general equipment and service rendered by the first twelve plants considered. The identity of the plants is withheld, in most cases by request, thus making available more complete and valuable data. These plants are located in centers ranging from 2000 to 20 000 inhabitants, and, in most cases, where the cost of

fuel is high. The equipments average about 300 brake horse power capacity and operate every standard form of generator for arc and incandescent lighting and for railway or general power service. All the generators are belted, the majority directly, but a few through the medium of a jack-shaft, the latter arrangement being employed in order to obtain the desired flexibility of service without installing a number of engines of small size.

Plants 13 to 15 are somewhat larger and generate polyphase power for industrial works. These three plants average approximately 570 brake horse power and the units are all direct-connected and run in parallel. Results of operation have been ob-

Typical Belted Station, with Jack-shaft.

tained from plants 1 to 11 inclusive, the first and last furnishing excellent data upon the comparative economy of the present gas-engines and the steam-engines which were replaced.

In general, the character of electrical equipment is not all that could be desired for furnishing results of great accuracy; but owing to the more or less uncertain calorific value of the fuel-gas used, errors of a few per cent. in particular cases will not have much effect upon the general result. In any event, the average cost of power charged against the station is the desired figure.

Service Requirements.—In considering the subject in hand from an unbiased standpoint, it is important to enumerate the

qualifications imposed upon the gas-engine, in order to determine its actual merits.

1. Continuity of service at any cost.

2. Simplicity of operation, conducing to the above and securing low cost of attendance.

3. Reasonable cost of equipment.

4. Economy of fuel and supplies.

1. A 65-h.p, two-cylinder vertical engine of the type employed in the plants here considered has made the following record:

Load		Fan Blower.	
Total elapsed time		8472 Hours.	100.0%
Hours run		8230 Hours.	97.0%
HOURS SHUT DOWN.			
Changing igniters	38 Hours.	0.45%	
Taking up bearings	13 "	0.15%	
Painting	179 "		
Repairing blower	5 "		
Changing gas supply	7 "		
Total	—	242 Hours.	3.0%
Ditto chargeable to engine			0.6%

During this period the engine ran, without stopping, 1157 hours and was then shut down to repair a broken belt.

In a pumping station located on the Allegheny, a short distance from Pittsburg, five 85-h.p. engines of the same type operate regularly at full load through the week without stopping, except on Sunday, when the units are shut down in rotation for inspection and repair. Each engine operates from 96 to 98% of elapsed time. It is needless to state that such service would not be required in central-stations, as reserve-capacity should be available for use during peak-loads. In the present exhibit, the majority of the plants operate from 18 to 22 hours per day, giving ample time for inspection and repair, even if no reserve-capacity were provided.

2. The skill required for operating a gas-plant is apparently no greater than for a steam-plant. In several instances where the latter have been replaced, the old employees have been retained. In newly-established plants steam engineers have invariably taken charge after short preliminary instruction from the builders' erecting engineer.

In plant No. 11, weekly inspection of bearings, igniters, and valves were at first carried out. This was found to be unnecessarily frequent and is now done once a month. The cylinders are

inspected occasionally throughout the year. This plant, 800-h.p. capacity, is operated by three day men and one night man, ten hours to a shift. The former steam-plant, about 500-h.p. capacity, required two day men and one night man, 12 hours to a shift.

3. In cost, the gas-engine equipment is quite comparable with that of a steam plant. The engine itself costs more than a steam-engine of corresponding size, on account of the increase in metal required by the higher pressures dealt with. With the cost of condensing machinery charged to the steam-engine, however, this disparity is much reduced. With natural- or illuminating-

Typical Belted Station

gas supply available, the cost of equipment would fall considerably below that of a steam equipment of boilers, engines, condensers, heaters, pumps, etc. In the case of a producer-gas plant installed to supply the gas-engines, the cost of the respective equipments, each of 1000-h.p., is nearly at a parity, depending somewhat upon the gas-storage capacity provided. This, however, amounts to much less than electric storage. For producer-gas the former costs in the neighborhood of $7.35[1] per h.p. and the latter $100. Considering the increase in productiveness of labor, which is stated by a prominent gas-engineer to be

1. $100 per 1000 cu. ft.

fully 100% (owing to the fact that one man can handle twice the amount of coal), the advantage, if any, held by the steam-plant, disappears.

4. In economy of fuel, the gas-engine admittedly has no rival. The present limit of steam-engine practice is 10 lb. water per i.h.p, or 11 lb. per b.h.p. With an evaporation of 10 lb. of water per lb. of good coal (14 000 B.t.u. per lb.) a performance of 1.1 lb. coal, or 15 400 B.t.u. per b.h.p. is realized. The gas-engine at present delivers, at full load, a b.h.p. upon 10.5 to 11 ft. of gas (of 900 to 1000 B.t.u. per cu. ft. calorific value) which is equivalent to 10 000 to 11 000 B.t.u. per b.h.p.; the Fig. on page 245

Typical Direct-Connected Station.

shows a typical test-log upon a 550-h.p. engine of the three-cylinder vertical type, employing the four-stroke cycle. The thermal efficiency shown is the true or " kinetic " efficiency, viz.:

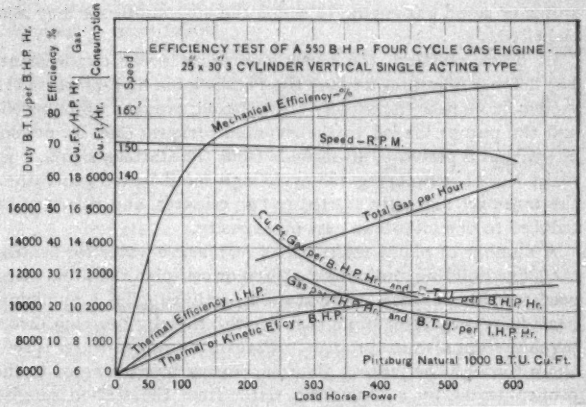
$$\frac{\text{Output}}{\text{Input}} = \frac{\text{B.t.u. equivalent of work done}}{\text{B.t.u. value of gas}}$$

At full load this appears as 25%. Considering the comparative remoteness of the theoretical limit of gas-engine efficiency, and the fact that the theoretical efficiency of a steam-engine working between the usual units of 150 lb. boiler and 3 lb. condenser-

pressure has already been exceeded, there appears to be an encouraging future for internal combustion motors.

Advantages.—The advantages of the gas-engine for central-stations may be summarized thus:

1. Minimum fuel and heat consumption.
2. Light load efficiency higher than steam-engine of corresponding size.
3. Low cost of operation and maintenance.
4. Simplification of equipment.
5. Small number of auxiliaries required.
6. Absence of " standby " losses.


EFFICIENCY TEST OF A 550 B.H.P. FOUR CYCLE GAS ENGINE
25 x 30" 3 CYLINDER VERTICAL SINGLE ACTING TYPE
Duty B.T.U. per B.H.P. Hr.
Efficiency %
Gas Consumption Cu.Ft./H.P. Hr.
Cu.Ft./Hr.
Speed
Mechanical Efficiency—%
Speed—R.P.M.
Total Gas per Hour
Cu. Ft. Gas per B.H.P. Hr. and B.T.U. per B.H.P. Hr.
Gas per H.P. Hr. and B.T.U. per I.H.P. Hr.
Thermal Efficiency - I.H.P.
Thermal or Kinetic Effcy - B.H.P.
Pittsburg Natural 1000 B.T.U. Cu. Ft.
Load Horse Power

7. Quick starting.
8. Waste heat in jacket-water suitable for building heating.
9. Ease of extending equipment.
10. Absence of high-pressure except in engine-cylinder. No danger from explosion outside, as a mixture of proper proportions is required.
11. Power can be stored during light loads at small cost in the form of gas in holder.
12. Subdivision of units more easily accomplished, yielding higher all-day economy.

An important source of economy in gas-plants is the fact that

as soon as an engine is shut down, all heat-losses cease. Also, during operation no heat is lost by the gas in transit from the producer, and the plant is not hampered by inefficient auxiliaries such as steam-pumps, condensers, return-traps, etc., all of which largely increase the general complexity of the system. Steam-pipe and cylinder-condensation losses, radiation, leakage in piping and fuel-loss in banking fires, have no parallel in the gas-plant. The only auxiliaries required are the igniter-generators, and air-compressors. The former are negligible as affecting the economy of the station, and the latter operate at full capacity at regular intervals. In cases where artesian wells supply jacket-water, a pump is of course required, preferably operated by a motor or small gas-engine to which the air-compressor may also be belted.

In quick starting, the gas-engine fulfils every requirement. The 280-h.p. pumping units of the Philadelphia high-pressure fire system have been repeatedly started cold, brought up to speed, and the pumps loaded to the required pressure (300 lb. per sq. in.) within a period of 40 seconds from the starting signal. In plant No. 11, employing 133-cycle high-speed belted generators, the units are regularly started in two minutes, and this may be reduced to one minute in case of necessity.

A number of plants make use of hot jacket-water for heating the office building, ordinary cast-iron or coil-pipe radiators being used for this purpose. One station partly supplies a municipal heating system resembling the Yaryan, thereby deriving direct revenue from a waste product. Part of the return-water is sent again through the jackets, the temperature being lowered to the proper degree by adding fresh water from the station supply-main. Station No. 14 returns hot jacket-water to a large cistern where it partially cools and is again pumped through the jackets emerging at a temperature of 200° fahr., before being discharged into the sewer. As return water from a heating system is also discharged into this well, a small amount of cold water from artesian well or city water system is added from time to time to reduce the general temperature of the circulating system. In another plant, the jacket-water is utilized in winter for warming the water in the gas holders to prevent freezing. This was formerly done by using live steam from a boiler used in making water-gas. It is estimated by the manager that a saving of $250 per year is effected. In locations where water is expensive, a small cooling tower may profitably be installed to cool the jacket-water which may then be saved.

In the matter of parallel operation of alternating-current generators, plants 13, 14, and 15 have been distinctly successful, particularly in view of the variable character of load incidental to large industrial works operated by induction motors. All the units are of the direct-connected type with standard fly-wheels. A spring-coupling provides a flexible connection between engine and generator, to absorb cyclical speed variations. The usual copper dampers on the pole pieces assist in preventing hunting. In general, a low frequency seems to be desirable, with high peripheral speed and moderate reactance in the generator to assist in damping current fluctuations. The suddenness of the impulse in a gas-engine cylinder offers, to be sure, greater difficulties than in the case of a steam-engine, but the remedy has apparently been found.

Fuel Gas.—Several distinct fuel-gases suitable for gas-engine use are available. When reduced to calorific values per foot of explosive mixture of proper constituency, the ratings are nearly equal:

		Approximate B.t.u. per cu. ft.	
		Gas.	Mixture.*
1.	Natural-gas	1000	91.0
2.	Coal-gas	650	91.7
3.	Water-gas	300	88.0
4.	Carburretted water-gas	600	92.0
5.	Producer-gas	120 to 145	60 to 68
6.	Coke-oven gas	600	90.0
7.	Blast-furnace gas	90	53.0

The power to be developed by an engine of given proportions does not therefore vary within appreciable limits, except on producer-gas and blast-furnace gas when larger engines are required, or larger cylinders on the same engine frames. The rate of combustion is less rapid with these than with other gases, due to the large amount of inert gases such as N and CO_2 present in the mixture. The compression may, however, be carried much higher without risk of pre-ignition or "back-firing," thus increasing the efficiency of the cycle. With water-gas the high percentage of hydrogen occasions quicker combustion and higher flame temperatures with so considerable a tendency to pre-ignition and back-firing that this gas is not well adapted to gas-engine work.

In water-gas plants a great saving may be made and the gas rendered much more suitable for the operation of gas-engines

*A. M. Gow, Eng'rs. Soc., West Penna.

by providing additional holders for the air or blast-gas made during the period when the producers are under blast. This gas is equivalent in calorific value to blast-furnace gas—90 B.t.u. per cu. ft.—and is generally allowed to go to waste. It may, however, be used to great advantage for power purposes, either alone or mixed with a proportion of water-gas which it renders less snappy and thereby better suited for use in gas engines. In fact, by this means a gas is obtained similar in many respects to the producer-gases made by operating a producer continuously with combined steam-and air-blasts.

Leaving out of consideration the by-product, or waste coke-oven and blast-furnace gases, as occupying a field of power-development somewhat foreign to the subject in hand, producer gas offers at present the greatest possibilities in the field of power for use in manufacturing centers. This is due to its comparative cheapness, simplicity of installation and general efficinecy when gas for power purposes is alone considered.

A comparison of the approximate thermal efficiencies of the various processes gives the following results:

Coal-gas (without coke)	24%
Coal-gas (with coke)	60%
Water-gas	60%
Water-gas, special quick-blast	75 to 80%
Producer-gas	80 to 85%

Assuming the calorific value of coal as 14 000 B.t.u. per lb. and the efficiency of the gas-making process 80%, the heat available at the engine is 11 250 B.t.u., which is equivalent to about one b.h.p. This duty, one b.h.p. per lb. of coal, should therefore be expected from a well-equipped gas-power plant.

Station Economy.—Returning to the consideration of the plants under exhibit, the average station economy observed is shown in Table 2. Averages for several month's operation have in most cases been given so that the results represent the efficiency of the entire station, day in and day out, with various generating outfits running at varying load-factors, and including errors of measurements encountered in every-day operation. Although in some cases "over-dynamoed," the engines are generally underloaded and frequently so much so that good economy could hardly be expected. The average gas consumption per kw-hr. is 39.0 cu. ft. Assuming an average calorific value of 625 B.t.u. per ft. for coal-gas, water-gas or mixed-gas, the heat consumption is 24 400 B.t.u. per kw-hr., 18 200 B.t.u. per

e.h.p-hr, and 14 500 B.t.u. per brake h.p-hr. The average cost of gas charged to the engine is 33.9c per 1000 cu. ft., which is in nearly all cases considerably above the cost in the holder to companies operating both plants, with the result that the gas works realizes a handsome profit from the electric station in addition to the decrease in cost per unit with increased production. This point will be brought out later. Assuming an average produc-

TABLE II. COST OF OPERATION.—FUEL ONLY.

Plant Number.	Character of Load.	Kind of Gas.	Per cent. of total Gas Generated, used for Engines.	Manufacturing Cost. Gas. Cents per 1000 cu. ft.	Cost Charged to Engines. Cents per 1000 cu. ft.	Gas per kw-hr. at Switchboard.	Cost per kw.		Remarks.
							Gas Only.	% Steam Station.	
						ft.		%	
1	Railway	Mixed	54	18	37.57	43.75	1.65	..	Av. 6 mo.
						28.40	1.07	81	All-day run.
					at 18	46.57	0.84	63.5	Gas at cost.
2	Arc.	Coal.		18	18	33.64	0.61	24.5	Av. 4½ mo.
3	Incan.	Coal.	31	..	62	53.2	3.3	..	Av. 6 mo. 1902.
4	"	Water.	30	..	59.3	41.6	2.46	..	Av. 20 mo. 1901–1902.
5	Arc. and incan.	Mixed.	37.5	..	34.6	..	..	..	Output not metered.
6	Incan.	Coal.	26	..	39.8	48.4	1.93	..	Av. 9 mo. 1902.
8	"	Coal.	5	19	33	28.5	0.94	..	Night run 65% rating.
9	"	Mixed.	19.5	..	29.5	41.7	1.22	..	Av. 6 mo. 1902.
10	"	Coal.	15.0	..	20	41.9	0.98	..	Av. 19 da. Aug. '02.
11	Incan. and Arc.	Natural.	100	10	15.0	12.4	0.18	..	Special test.
				10	16.0	21.5	0.34	26	Av. 6 mo.
	Average.	..	..	..	33.9	39.0	1.4	..	

Average cost per kw-hr. at 20c, Gas (excluding No. 11).....0.828
" cu. ft. Gas. per kw-hr.....39.0

tion-cost of 20c per 1000 cu. ft., the average cost of power is 0.83c per kw-hr., equivalent to 0.495c per b.h.p-hr. at 80% combined efficiency.

The comparative cost of steam and gas-power is well shown in Tables 3 and 4. In Table 3, two independent stations were operated during 1902, together with the gas works. The cost of coal in the steam plant was 1.38c per kw-hr. against 0.75c per kw-hr. in the gas plant, representing a saving of 45.5%, although

the cost per 1000 B.t.u. of gas was 3.4 times that per 1000 B.t.u. of coal. Assuming calorific values of 14 000 and 625 B.t.u. per lb. and cu. ft. respectively, 92 000 B.t.u. were required per kw-hr. in the steam station, against 29 100 in the gas station, or a saving of heat in the latter of 68.5%.

TABLE III. PLANT NO. 1.

COMPARATIVE OPERATING ECONOMY.

Load.	Steam Station 1250 i.h.p. Averages for 6mo. Apr.-Sept.		Gas Station 685 b.h.p. Averages for 5 mo. May-Sept.	
	Railway, Incandescent, Arc.		Railway.	
	1901.	1902.	1902.	
Kw-hr. per mo.	.....	122 733	Kw-hr. per mo.	39 508
Lb. coal	761 058	802 507	Cu. ft. Gas	1 726 400
Per cent. ash	8.2	7.7		
Lb. coal per kw-hr.	.....	6.55	Cu. ft. Gas per kw-hr.	43.75
Cost coal per ton, f.o.b.	.....	4.02	Gas charged per 1000 cu. ft.	37.57c
Handling	.....	.19	Price gas per kw-hr.	1.65c
Total	.....	4.21	Cost gas, actual	17.2c
Cost coal per kw-hr.	.....	1.375c	Actual cost kw-hr.	75c.
			Per cent. saving cost per kw-hr. over coal.	45.5%
Watt-hours per lb. coal —a.m.	138.20	134.65	Watt-hours cu. ft. Gas —a.m.	24.33
Ditto—p.m.	164.40	166.02	Ditto—p.m.	21.40
Ditto—24 hr.	159.97	159.08	Ditto—24 hr.	22.23
B.t.u. per lb., estimated.	14 000	14 000	B.t.u. per cu. ft., est.	625
Watt-hours per 1000 B.t.u.—24 hrs.	.....	11.35	Watt-hours per 1000 B.t.u.—24 hrs.	35.6
B.t.u. per kw-hr.	.....	92 000	B.t.u. per kw-hr.	29 100
B.t.u. per e.h.p-hr.	.....	68 600	B.t.u. per e.h.p.	21 700
B.t.u. per b.h.p-hr. at 80%	.....	55 000	Per b.h.p. at 85%	18 450
			Per cent. saving heat.	66.5%

SPECIAL TEST.—GAS STATION.

All-Day Run:		*Five-Hour Run.*	
Max. Watt-hrs. per cu. ft. Gas.	35.3	Max. Watt-hr. per cu. ft.	40.9
Cu. ft. Gas per kw-hr.	28.40	Cu. ft. Gas per kw-hr.	25.0
" " " " e.h.p-hr.	21.20	" " " " e.h.p-hr.	18.6
" " " " b.h.p-hr.	18.02	" " " " b.h.p-hr.	16.65
B.t.u. per b.h.p.	11 250	B.t.u. per b.h.p.	10 400

Note.—Both plants run 15 to 18 hours per day. Steam equipment consists of compound condensing engines and water-tube boilers. Average load factor of steam station higher than gas station.

In Table 4 the output was not measured, but the costs indicate the general balance of economy on the side of the gas station. The steam plant started operation on natural-gas at 10c per 1000, with a minimum of $3000 per year. It employed horizontal return tubular boilers fired by gas. One year after starting the

gas plant, this minimum was reached and the company is now paying at the rate of over 16c per 1000 ft. The saving in total operating cost amounted to 40.5%. In the face of a 30% increase in station output, the gas consumption has been reduced by 93%. Previous to the replacement of the steam-equipment, an economy-test was run on the station, throughout 24 hours. The gas consumption at the boilers was 51.09 cu. ft. per i.h.p., developed at the engines, equivalent to about 86 cu. ft. per

TABLE NO. IV. PLANT NO. 11.

COMPARATIVE COST OF OPERATION.—STEAM ENGINES VS. GAS ENGINES ON NATURAL GAS.

Year.	Gas ft.	Labor.	Repairs.	Oil and Waste.	Total.	Remarks.
		Steam Plant.		Gas-Fired Boilers.		575 i.h.p.
1897	9753.20	9725.26	300.00	1485.06	....	Gas rate, 10c per 1000 cu. ft.
1898	9320.70	8258.33	400.00	306.14	19 924.34	minimum reached in 1900. Avg. 1902, 15.9 per 1000 cu. ft.
		Gas Engine Plant.				800 b.h.p
						Increase Revenue.
1899	6318.92	6828.74	239.85	533.56	....	1897 — %
1900	3000.40	6782.01	499.09	592.92	....	1898 5.75
1901	3000.00	7678.83	196.90	407.01	....	1899 7.5
1902	3000.00	7626.87	261.04	379.70	....	1900 13.5
						1901 11.0
						1902 18.5
					11 836.41	Increase load 1898–1902, —30%.
				Saving—	8087.93	= 40.5%.

Steam.....$36.40 per yr. per h.p-capacity of station.
Gas.....14.80 " " " "

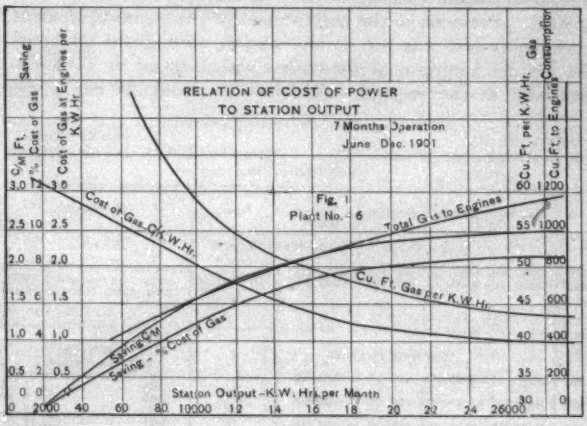
Saving.....$21.60 = 59.4%

ECONOMY TEST.

Steam Station:	*Gas Station:*
1898–24 Hours.	
Gas per i.h.p-hr.....51.09 ft.	Gas per kw-hr., Av. 6 mo...21.50 cu. ft.
" " kw-hr.....86 "	Calorific value gas, 1175 B.t.u. per cu. ft.

kw-hr. All engines were of the simple high-speed type, running non-condensing. A short preliminary test of the gas plant after installation showed an economy of 12.31 cu. ft per e.h.p-hr. During the six months ending August, 1902, the total gas consumption of the station, including heating, was 23.8 cu. ft. per kw-hr. Deducting approximately 7.5% for heating, the net consumption was 21.5 cu. ft., which is about 24% of that recorded on the steam station. It is equivalent to 12 cu. ft. per b.h.p. or a duty of 14 100 B.t.u. per b.h.p.

The gross station economy in the case of plant No. 6 is shown on Fig. 1. These observations were taken when the station was first started and operating under an extremely low load-factor.


RELATION OF COST OF POWER
TO STATION OUTPUT
7 Months Operation
June Dec. 1901
Fig. 1
Plant No. - 6
Saving
Cost of Gas at Engines per K.W.Hr.
Cost of Gas
Cu. Ft. per K.W.Hr. Gas Consumption
Cu. Ft. to Engines
Cost of Gas Cts K.W.Hr.
Total Gas to Engines
Cu. Ft. Gas per K.W.Hr.
Saving Cts
Saving - % Cost of Gas
Station Output - K.W. Hrs. per Month

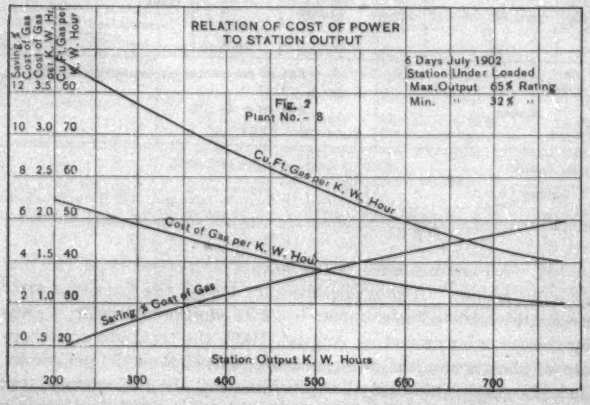

RELATION OF COST OF POWER
TO STATION OUTPUT
6 Days July 1902
Station Under Loaded
Max. Output 65% Rating
Min. " 32% "
Fig. 2
Plant No. - 8
Saving % Cost of Gas
Cost of Gas per K.W. Hr.
Cu. Ft. Gas per K.W. Hour
Cu. Ft. Gas per K. W. Hour
Cost of Gas per K. W. Hour
Saving % Cost of Gas
Station Output K. W. Hours

Fig. 2 shows similar results upon station No. 8, which also operates considerably under rating. Both curves show the decrease in cost of gas at the gas works, due to the increase in works

output, necessitated by the electric station. The results may be considered as representative of conditions about as unfavorable to high economy in the prime mover as is usually encountered. Table No. 5 gives the operating cost of plant No. 9—135 h.p. capacity—for six months, during 1902. The average cost of gas is 1.22c per kw-hr. and the total operating cost 3.18c per kw-hr.

The above data shows in a general way the results that may be accomplished by gas-power plants, even though running under a burden of expense for fuel that would be quite out of the reach of steam plants. It goes without saying that much better results are obtainable in a plant of considerable size, of modern design and furnished with reasonably cheap fuel-gas.

TABLE V. PLANT NO. 9.

OPERATING COSTS GENERATING STATION.

Month, 1902.	Kw-hr. Generated.	Gas to Engines. 1000 cu ft.	Works Cost Materials per 1000 cu. ft.	Cu. ft. per kw-hr.	Cost Gas per kw-hr.	Total Cost Labor and Materials	Operating Cost per kw.	Remarks.
			c.		c.	$	c.	
Jan.....	5465	187.6	32.2	34.4	1.1	149.07	2.74	Av. 194%.
Feb.....	4489	170.7	32.5	37.0	1.2	145.84	3.24	Total gas
Mar.....	4186	180.2	31.0	43.0	1.34	146.02	3.5	generated
Apr.....	4670	226.6	31.0	48.5	1.5	168.31	3.61	used by
May.....	5124	227.1	28.0	43.4	1.21	161.70	3.16	engines.
June.....	5246	231.3	22.5	44.0	0.99	153.73	2.93	
Average..	....	....	29.53	41.7	1.22	....	3.18	

Combined Gas and Electric Stations.—The theory of increase of profits from the operation of combined gas and electric plants is based upon the fundamental principle of reduction in cost per unit with increased output. If the net saving is sufficient to cover fixed charges upon the electric station, the way is clear to reap a double revenue, one from the electric station operating at a cost far below its steam-driven competitors, and the other from the gas station operating at a lower cost of production than before. The balance may of course be applied proportionately to the disbursement of fixed charges on both stations. It is usually the gas station that reaps the profit at the expense of the electric station. An adjustment of gas and electric rates can easily be made to prevent embarrassing competition.

Fig. 3 shows the cost of coal-gas, water-gas and mixed-gas for approximately 500 gas plants in the United States.[1] The curves were determined by the method of moments from a "shot-gun" diagram, and bring out the following points:

1. Cost per unit decreases as output increases, most rapidly in coal-gas plant and less rapidly in water-gas plants.

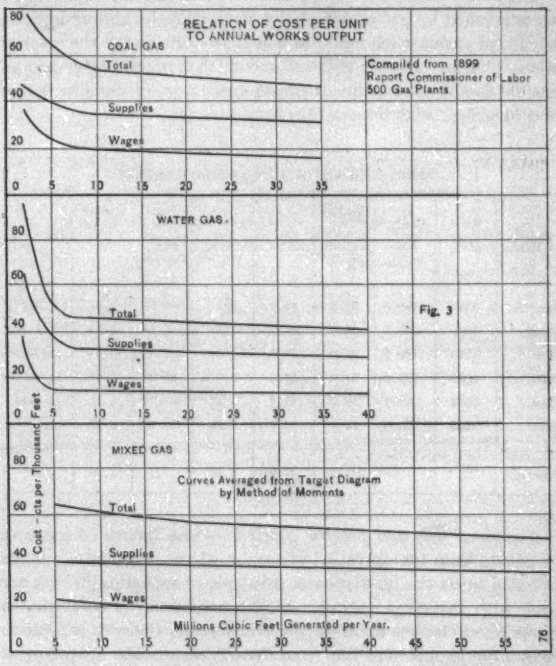


Fig. 3

2. Decrease in cost per unit in small plants of two to ten million cu. ft. per year output is very marked, being greatest in water-gas plants and least in mixed-gas plants.

3. The greatest opportunity for increasing revenue from combined gas and electric stations appears to be in the case of small

1. Report of the Commissioner of Labor on Gas and Electric Plants, 1899.

coal and water-gas plants under ten million cu. ft. output. The smaller the plant, the greater the profit.

In Table No. 2, Plants 1 to 10 inclusive operate combined gas and electric works and all successfully. Although production-cost[1] of gas is not in all cases available, in most cases the power-gas is charged to the engine at such a rate as to insure a handsome profit to the gas works. Table No. 6 shows results obtained from Plant No. 1. In this case the electric-plant was charged with gas at twice the cost of production. The gas works also realized a saving of 5.7c per 1000-cu. ft. nominal, or 10.3c actual, as a result of the increased output due to the gas-engines, which is 60% of the present production cost. The total saving thus

TABLE VI. PLANT NO. 1.
PROFIT FROM COMBINED OPERATION OF GAS STATION WITH GAS WORKS.
Gas Works, Total Prdouction, Year 1901–2.....38 241 000 cu. ft., – 10 100 ft./ton.

Costs.	Cost.	Cents per 1000 cu. ft.
Coal, at $4.03, 3780 tons	$15,208.70	40
Bench fuel	3,381.97	8.8
Labor	2,473.50	6.61
Repairs	676.11	1.63
Miscellaneous Expenses	184.90	0.48
Total Cost Gas	$21,945.18	57.56
Residuals.		
Coke at $6.00, 2375 tons	$14,250.00	37.20
Tar at 3.7c., 31 750 gal.	1,172.00	3.18
Total Receipts—Residuals	15 422.00	40.38
Net cost gas		17.18c per 1000 cu. ft.

Cost gas charged against works, Av. 4 months	67.15c	per 1000 cu. ft.
" " " " gas engines, av. 6 months	37.67c	" " "
Decrease cost gas due to increased production, actual	5.68c	" " "
" " " " (basis of equal cost coal) See Table VII	10.31c	" " "
" " in per cent. of works cost	15.4%	
" " " engine "	27.4%	
Profit to gas works from engines	20.49c	per 1000 cu. ft.
" " " " greater output	10.31c	" " "
Total profit, due to gas engines	30.80c	" " "
" " " " " " per cent. works cost	45.8%	

amounted to 30.8c per 1000-cu. ft, nearly twice the production cost, and but little under the cost charged to engines.

Table No. 7 shows the actual rate of decrease per month. In the last column results are reduced to a basis of equal cost of coal; viz., that of 1901.

Table No. 8 gives results in plants where similar data was available. The average saving recorded, due to gas-engines, was 5.2c per 1000 cu. ft, or 6.8% of initial works cost.[2] This, how-

1. Revenue from sale of residuals deducted.
2. Residuals not deducted, maintenance included.

TABLE VII. PLANT NO. 1.
REDUCTION IN COST PER UNIT WITH PRODUCTION.
Mixed Gas.

	1000 cu. ft. Generated.			1000 cu. ft Increase.	% Increase.
	1901.	1902.			
April	4115.5	5183.9	....	*1068.4	26
May	3028.2	6612.4	....	3584.2	118
June	3044.1	6845.3	....	3801.2	125
July	4163.3	7176.6	....	3013.3	72.5
Aug	4431.5	7775.0	....	3343.5	75.5
Average	3666.8	7102.5	....	3435.7	97.75

	Total Works Cost cents per 1000 cu. ft. Gen.			Decrease Cost Nominal.		Decrease Cost at 1901 Coal. Actual.	
	1901.	1902.	Cost at 1901 Coal.	Cents per 1000 cu. ft.	%	Cents per 1000 cu. ft.	%
Apr	62.63	66.59	61.60	-3.86	-6.15	1.03	1.67
May	65.90	61.91	57.20	3.99	6.45	8.70	13.2
June	68.90	62.67	57.90	6.23	9.05	11.00	16.0
July	66.47	60.05	55.60	6.42	9.65	10.87	16.35
Aug	67.40	61.32	56.75	6.08	9.02	10.65	15.8
1901 coal $3.75 1902 coal 4.02	67.15	61.49	56.86	Av. 5.68	8.54	10-31	15.34

*Gas Station operating light for testing out. April results not considered.

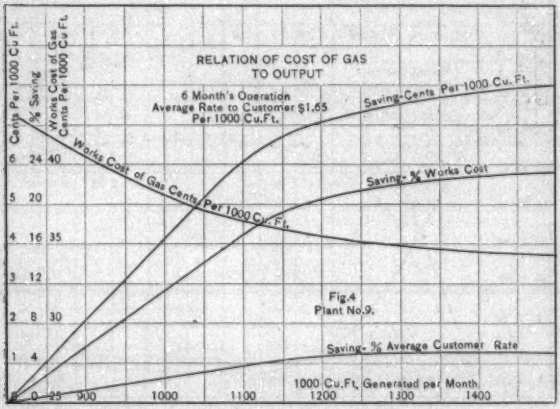
TABLE VIII.
COMPARATIVE COST OF GAS AS AFFECTED BY PRODUCTION.

Plant Number.	Output in cu. ft. per mo. before using Gas Engines.	Output in cu. ft. after Gas Engines were used.	Increase in Output.	% Increase.	Works Cost Gas. Before	Works Cost Gas. After	Saving. Cents per 1000 cu. ft.	Saving. % Cost of Gas before Engines were used.	Remarks.
1	3666.8	7102.5	3435.7	97.75	67.15	61.49	5.68	8.54	Per mo. Av. 4 mo.
	3666.8	7102.5	3435.7	97.75	67.15	56.86	10.31	15.34	Estimated basis 1901 cost coal.
2	2250	3250	1000	44.5	..	18	8-10	..	Net charges, estimated.
3	590	924	334	56.5	65.6	63.99	3.06	5.5	Per mo. Av. 8 mo.
6	2192	4139	1947	89	42.5	39.8	2.7	6.4	Per mo. Av. 8-12 mo.
10	....	....	....	50	..	..	5.0	...	20% Inc. cost of coal.
						Av....	5.2	6.8	

ever, is less than the actual saving by reason of the general increase in cost of coal at the time the last observations were taken, due to general stringency of fuel.

A comparison of the then prevailing market prices for fuel with the normal shows an increase of 24% in coal and 45% in coke.[1] Applying to Table No. 8, the percentage difference in saving due to difference in fuel-cost observed in Plant No. 1; viz., 15%—the average per cent. saving is 7.8% of works-cost—a material saving in any plant. This, of course, applies directly to the gas as distributed to customers.

These results, for consecutive months, are shown graphically in Figs. 4 and 5, which represent saving due to increased produc-



tion, part of which is traceable to the electric-plant and part to consumers. In Plant No. 9 a saving of 24% was realized, and in Plant No. 6 the remarkable amount of 92% of initial works cost.

In order to bring out clearly the character of this saving due to increased production, the following case has been estimated along the lines indicated in the preceding pages. A ten-million-

1. The comparative market prices for fuel in the case of ten of the above plants averaged $3.63 and $5.10 f.o.b. works for coal and coke respectively, under normal conditions. The corresponding prices during 1902 averaged $4.50 for coal and $7.41 for coke, or an increase of $0.87 and $2.41 over normal for coal and coke respectively. See Table 9.

foot plant has been taken generating gas at 40c per 1000 cu. ft. works cost, including coal, bench fuel, labor, repairs, and miscellaneous material, residuals not deducted. Fixed charges have purposely been omitted. The gas is charged at works cost to the electric station It is assumed that the cost of gas for this plant, previous to absorption of the electric-plant, was 50c per 1000 cu. ft, and that the electric-plant generates electricity at twice the fuel cost, 3.2c per kw-hr. During normal operation with an output to the electric-plant of 30%, of the total amount of gas generated, the total net revenue was about $13 300; 45% of which was due to the electric station and 55% to the gas

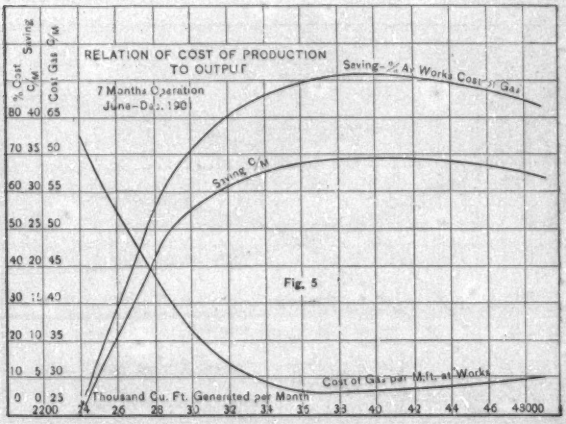

% Cost Saving C M
Cost Gas C M
RELATION OF COST OF PRODUCTION TO OUTPUT
7 Months Operation June–Dec. 1901
Saving-% Av. Works Cost of Gas
Saving C M
Cost of Gas per M ft. at Works
Thousand Cu. Ft. Generated per Month
80 40 65
70 35 50
60 30 55
50 25 50
40 20 45
30 15 40
20 10 35
10 5 30
0 0 25
2200 24 26 28 30 32 34 36 38 40 42 44 46 48000

Fig. 5

station. The operating costs will then amount to 46.4% of the net revenue.

Comparing the operations of the gas station *per se*, previous to and following the acquisition of the electric station, there is a net revenue of $5835 and $7344 respectively, or an increase of $1509; 25.8% of the original revenue. Figuring in the saving of 10c per 1000 cu. ft. due to increased production, the total increase amounts to 43% of the net revenue upon the original gas station.

Considering, finally, the combined works, the increase is $7449, or 127% of the original revenue, and adding again the saving 10c

TABLE IX.

FUEL COSTS AND PRICES PAID FOR RESIDUALS.

Plant No.	Gas Coal			Steam Coal.			Coke.			Tar	Remarks.
	Normal.	1901	1902	Normal.	1901	1902	Normal.	1901	1902	Normal	
										c.	
1	3.75	4.02	4.02	....	3.83	..	6.00 (4.96 charged against works.)	..	7.00 7.50	3.7	19c. per ton handling 1902 hard coal.
2	..	3.75	4.55	....	3.75	4.55	....	5.00	7.50	3.5	
3	3.00	4.00	5.00	3.00	..	5.00	5.00	..	6.00	3.5	Coke 8.00 outside.
4	..	..	....	2.50	..	..	5.70	..	8.60	..	Use coke only.
5	..	4.55	4.82	....	..	..	5.00	5.50	7.50		Av. frt. rate from mines $1.50 ton.
6	3.55	4.20	3.85 4.35	....	..	..	10c. bu.	..	..	..	Coal by contract.
7	..	..	3.75	....	..	..	4.00	..	7.50	3.5	
10	3.15	..	4.50	....	..	..	5.00	.	7.50	7.0	Coke 10c. bu. Ammonia 26c. per ton coal.
Av..	3.63	..	4.50	....	..	..	5.10	..	7.41	..	

Av. Increase: $0.87 = 24%. Av. Increase 2.31 = 45%.

TABLE X. GAS WORKS YIELD.

Plant No.	Yield.			Kind of Gas Mfd.	Remarks.
	Gas. cu. ft. per ton.	Coke lbs. per ton.	Tar gal. per ton.		
1	9700 10 100 10 000 10 500	1260 1350	7.5 8	Mixed. Coal.	
2					
3	10 500	1275	8	Coal.	
4	....	....	....	Water.	Coke used.
5	10 000	1350	....	Mixed.	Bench fuel 300 lb. per ton.
6	9000	....	....	Coal.	
7	9700	1300	8	Mixed.	Bench fuel 300 lb.
8	....	870	10	Coal.	
10	Ammonia 26c per ton.				
Av.....	9937 ft.	1233 lb.	83. gal.		

per 1000 cu. ft., the total increase is 145% of the net revenue of the original gas works.

Although these percentages will be considerably reduced by the consideration of investment charges, depreciation, sinking fund, etc., the fact remains that the saving due to combined operation is material and should appeal particularly to companies operating independent gas and electric generating stations.

*OPERATING COSTS AND PROFITS OF A TYPICAL GAS-ELECTRIC WORKS.

ASSUMPTIONS:

Output per year	10 000 000 cu. ft.
Gas per ton	10 000 "
Works-cost gas	40c per 1000 cu. ft.
Works-cost gas, before gas-engine used	50c " 1000 "
Cost at engine	40c " 1000 "
Coal	$3.75 per ton.
†Coke per ton, at $5.00 per ton	1230 lb.
Bench fuel per ton, at $4.00	300 "
Gas-tar per ton, at 4.5c	8.3 gal.
Line and meter loss, gas line	15%
Line and meter loss, electric system	10%
Average rate to gas customer, per 1000 cu. ft.	$1.25
Average rate to electric customer, per kw-hr.	12c
Electric plant consumption of gas, % total output	30%
Gas per kw-hr. at switchboard	40 cu. ft.
Fuel cost per kw-hr. at switchboard	1.6c
Works cost per kw-hr. at switchboard	3.2c

REVENUE:

Gas:

Gas to electric plant, 3000 cu. ft. at 40c		$1200
Gas for distribution, 7000 cu. ft.		
Gas for sale, 85%, 5950 cu. ft. at $1.25		7445
Total sale gas		$8645

Residuals:

Coke for sale, 465 tons	$2325	
Tar for sale, 8300 gal.	374	
		2699
Total sales, gas works		$11 344

(*) Fixed charges omitted from this estimate.

(†) In coal-gas plants the sale of residuals constitutes an important part of the total revenue, so important in fact that during times of high-priced fuel it pays to manufacture coal-gas rather than water-gas, and sell residuals. The average yield per ton of coal is shown in Table No. 10, viz.: 10 000 cu. ft. of gas, 1230 lb. coke and 8.3 gal. tar.

Electricity:

Kw-hr. generated 3000 cu. ft. / 40 cu. ft.	75 000	
Line loss 10%	7500	
Kw-hr. for sale	67 500	
Revenue from electric station		$100
Total revenue from works		$19 444

COST:

Gas:		
10 000 cu. ft. gas at 40c		$4000
Net revenue station, exclusive of fixed charges	$7344	
Electric:		
67 500 kw-hr., at 3.2c	2160	
Net revenue station, exclusive of fixed charges	$5490	
Total cost to combined works		$6160
Total net revenue to combined works		$13 284
Per cent. due to electric station		44.7
Per cent. due to gas station		55.3
Electric station per cent. of gas station		81.
Operating cost per cent. of net revenue:		
Electric station		36.3
Gas station		54.5
Works		46.4

COMPARISON OF COSTS, BEFORE AND AFTER INSTALLING ELECTRIC STATION.

Gas Station.

BEFORE.		AFTER.	
Revenue:			
Gas for sale, 5950 cu. ft. at $1.25	7445	5950 cu. ft. at $1.25	$7445
Residuals	1890	3000 cu. ft. at 40c	1200
		Residuals	2699
Total revenue	$9335		$11 344
Costs:			
7000 cu. ft. at 50c	3500	10 000 cu. ft. at 40c	4000
Net revenue	$5835		$7344
		Increase	1500
		Saving 10 000 cu. ft. at 10c.	1000
		Total increase	$2500
Cost % net revenue	60%	Cost % net revenue	54.5%
		Cost % net revenue plus saving	32.4%

GAS AND ELECTRIC WORKS.

BEFORE.		AFTER.	
Revenue	$9335	Total revenue, gas, electric, and residuals	$19 444
Cost	3500	Cost—gas and electric	6160
Net revenue	$5835	Net revenue	$13 284
		Increase	$7449
		Saving—10 000 cu. ft. at 10c	1000
		Total increase	$8449
Cost % net revenue	60%	Cost % net revenue	45.4%
		Cost % net revenue plus saving	43.0%

Discussion of Paper by J. R. Bibbins Entitled Gas-Power for Central Stations.

Ralph D. Mershon:—The speaker does not believe this paper gives a fair comparison of the relative value of gas-engines and steam-engines, in general, for electric work. A proper general comparison should include, not only the cost of fuel, but also the cost of depreciation, interest, repairs, and attendance charges. It is only when a full statement of the cost is given that true comparisons can be made. The speaker believes in the future of the gas-engine; in Germany, many plants, consisting of producers and gas-engines are now in use, and the number is increasing; the recent adoption of the "suction" generator has done much to hasten this development.

The author, on page 243, says that the cost of a 1000-h.p. plant for gas and steam is about the same. The speaker is of the opinion that the cost of a gas plant will be very materially greater, and hopes that the author can substantiate this statement by detailed figures. The speaker found in Europe that the calorific value of the various explosive mixtures used is generally much more nearly equal and is lower than shown in the table on page 247. He thinks also that the prices asked by American manufacturers for gas-engines are entirely out of reason, and that such excessive prices will retard the general use of gas-engines.

Philip Torchio:—The speaker is of the opinion that the very favorable results shown by Mr. Bibbins are due to the fact that he considers a small gas station; if he had based his comparisons on a larger station, the figures would not have been so favorable.

Herbert A. Wagner:—Unfortunately, all users of gas-engines cannot secure results as favorable as those cited by Mr. Bibbins. The speaker has recently removed a gas-engine plant and replaced it by steam-engines. The plant consisted of three 100-h.p. units, operating alternators and arc dynamos. The cost of operation, large at first, had increased to such an extent from year to year that the company was forced to make a change of some kind. It was decided to abandon gas-engines entirely. In the last year of the operation of this plant, the cost of energy was more than eight cents per kilowatt-hour; the largest single item was the cost of repairs and maintenance. In this plant, producer gas was generated solely for the gas-engines; the plant was run entirely apart from the gas-making plant.

H. G. Stott:—On page 253, the author states that "the average cost of gas is 1.22 cents per kilowatt-hour, and the total operating cost 3.18 cents per kilowatt-hour." The cost of fuel is then 38% of the total cost, or the other costs of operation are 62%. In the ordinary steam plant, the cost of fuel is probably 70% of the total cost. This difference of 32% of the total cost of operation represents, of course, the increased cost of maintenance and labor for the gas-engine plant. These figures illustrate the differences in the two kinds of plants.

J. R. BIBBINS (in reply to the Discussion):—The principal object of the paper is to place before you results and observations upon the operation of a number of gas plants of very moderate size and not to introduce comparisons with stations of larger output or with those operated upon producer gas, which of itself constitutes a separate and distinct field. The direct comparisons between steam- and gas-power plants have been confined to plants No. 1 and No. 11, upon both of which reliable data are available. The comparisons are, it seems to the speaker, perfectly legitimate, particularly in the case of Plant No. 1, where both steam and gas stations were operated simultaneously for the specific purpose of determining the relative economy; in both plants steam power has been replaced by gas power through "the survival of the fittest."

As to the comparative cost of steam and producer gas power equipment: leaving out of consideration the cost of holder capacity, the costs will be nearly equal. With this item included, the cost of the gas equipment is slightly in excess, depending upon the character of the producer employed—whether continuous or intermittent—and upon the requirements of the service—whether the power demand is reasonably constant or heavily fluctuating. The holder capacity to be provided is purely a matter of judgment and should be estimated in each individual case in a similar manner to steam-storage capacity in a steam plant. A prominent gas-engineer recently quoted the comparative cost of 1000-h.p. high-grade steam and gas plants as follows:

$100 per horse power for a steam equipment, consisting of compound condensing engines, electrical machinery, boilers, stokers, economizers, and coal-handling machinery; $125 per horse power for a gas equipment comprising high-grade engines electrical machinery, producers, coal-handling machinery and a 20 000-ft. holder, capable of supplying the plant at full load for about 20 minutes. If holder capacity is dispensed with in a producer plant and the engines simply draw their supply of gas directly from the producers under either slight pressure or suction, there is the risk of gas of non-uniform quality reaching the engine cylinder. Storage capacity obviates this to a large degree, and is evidently essential in the operation of electric plants where exact regulation is so much more important a requirement than, for instance, in driving blowing-engines by blast-furnace gas.

A possible explanation of the requirement of a higher grade of intelligence among European operators may be found in the character of engines used. Large engines are quite common abroad, due to long development and the great demand for cheap power. Many are of comparatively complicated construction and consequently require more-skilled attendants. It has been observed in the plants on exhibit that the grade of intelligence is a matter rather secondary to the personal prejudices of the

operators. The greatest difficulty encountered in breaking in new men was to overcome their prejudices. But, with knowledge of the construction and operation of the plant and its superiority from the standpoint of comfort and safety to employes, this prejudice disappeared and more efficient operation of the plant resulted.

In plant No. 1 the entire station was operated without a single interruption for a period of six months through a regular shift by one attendant, formerly a wiper in the steam plant. This man had never held an engineer's position.

In reference to the calorific value of the various mixtures given on page 247, the values are for theoretically perfect mixtures. More air is however sometimes required than is called for by a perfect mixture, which may result in the lower values referred to by Mr. Mershon. But the speaker believes that the calorific value of mixture of the leaner gases is generally much lower than for illuminating and natural gas, which seems reasonable on account of the inert ingredients of producer and blast-furnace gases.

The quantity of jacket-water required depends largely upon the quality of the supply. If it contains no chemical or vegetable impurities, so that deposits in the jackets will not occur, the cylinders may be run hotter than with impure water and consequently less water will be required. On the average, about 4000 B.t.u. per brake h.p. are carried away in the jacket-water and the quantity, therefore, depends upon the terminal temperatures, which in winter might easily range from 40° fahr., inlet, to 200° fahr. outlet, if the water is good.

The field for commercial heating by jacket-water is of course not comparable with that by exhaust steam, from the fact that the latent heat is not available as in the case of steam.

These figures represent the temperature range of "in and out" jacket-water, which may be secured with good water during cold weather. The rate of flow can be determined from these temperatures and the total heat to be removed by the jackets.

[Replying to a question.] There are two general methods of governing; viz., the hit-and-miss, and the method of throttling the charge. It is safe to say that the former is thoroughly unsuited for driving generators. The latter is employed in several different forms, each with many prominent representatives. The method that is widely employed in both American and European engines is that of throttling a mixture of constant quality, under which conditions the maximum fuel-efficiency may be retained at all loads.

[Replying to a question.] A considerable amount of experimental work has resulted in the employment of the spring coupling between engine and generator, and success seems to lie in this direction, together with the use of multi-cylinders. With flywheels of moderate capacity, a three-cylinder engine of the type shown gives a crank effort of such uniformity that the cyclical

variation, expressed in angular degrees, falls within standard specifications for steam-driven generating units. It is found, however, that the best results in parallel operation are secured with the flexible coupling which deadens to a large degree the suddenness of the impulse following combustion. In the three plants cited—13, 14, and 15—parallel operation is an accomplished fact. All three plants operate cranes, hoists, and shop motors (all of the induction type) and the load fluctuates constantly, often through a range of 100% in a few seconds. In general, it is not necessary in a plant of several units to provide all engines with spring couplings. One unit may have a solid coupling and will operate satisfactorily with the remaining spring-coupled units. With double-acting engines the difficulties in parallel operation are of course halved and further reduced in the ratio of the number of cylinders employed.

The data from which Mr. Stott draws conclusions are given in No. 9, a plant of only 135 h.p. The cost of power in plants No. 1 and No. 11 should rather be taken as representative of the economy to be obtained from a gas plant of moderate size. Mr. Stott also draws attention to the importance of labor and maintenance. In plant No. 11 these items aggregate 52% of the total operating cost of the steam station and 67.5% of the gas station. The increase in percentage is not due to acutal increase in operating cost, but rather to the decrease in the fuel item which renders the maintenance item the more conspicuous. The average maintenance cost for the steam station was $10 400 as against $8000 for the gas station of nearly double the capacity.

(COMMUNICATED AFTER ADJOURNMENT BY J. R. BIBBINS.)

Replying further to the discussion upon the comparative importance of fixed charges upon steam- and gas- plants: the following figures are obtained from Plant No. 11. The costs are expressed in terms of brake horse power per year of capacity of station, for the reason that accurate records of kilowatt-hour output are not at present available.

INVESTMENT.

Items.	Steam Plant.	Gas Plant.
Building and Real Estate	$17 000.00	$17 000.00
Steam Machinery, complete	51 000.00	
Gas " "		60 000.00
Total	$68 000.00	$77 000.00
Equipment cost per h.p.	139.00	96.25
Building " " "	35.00	21.25
Machinery " " "	104.00	75.00

FIXED COSTS.

Interest on investment, 5%.....	$3 400.00	$3 850.00
Depreciation, Building, 3%.....	390.00	390.00
" Machinery, 10%.....	5 100.00	6 000.00
Taxes, Insurance, Legal, etc.. 3%.....	2 040.00	2 310.00
Total fixed charges.....	$10 930.00	$12 550.00
Per brake h.p. per year.....	22.30	15.70
Net operating cost	36.40	14.80
Total operating cost.....	$58.70	$30.50
Saving.....	28.50 =	48%

Concerning the quantity of jacket-water required under ordinary conditions of operation, two cases are given below representative of summer and winter extremes. Assuming a duty of 11 000 per brake h.p-hour at the engine and 40% of the heat to be imparted to the jackets, the jacket-water will carry away 4400 B.t.u. per hour.

	Winter. Temp. of Water.	Winter. Sensible Heat per lb.	Summer. Temp of Water.	Summer. Sensible heat per lb.
Leaving jackets.....	200° fahr.	168 B.t.u.	200° fahr.	168 B.t.u.
Entering "	40° fahr.	8 B.t.u.	65° fahr.	33 B.t.u.
Range "	160° fahr.	160 B.t.u.	135°	135 B.t.u.
4400/160 = 27.5 lb. per h.p-hr.		4400/135 = 32.6 lb. per h.p-hr.		
Water per h.p.-hr. = 0.44 cu. ft.			0.52 cu. ft.	

A simple and efficient method of reclaiming the heat discharged in the exhaust is successfully used in one plant operating both steam and gas equipments. The exhaust gases are passed through a tubular heater resembling an ordinary feed-water heater. By shutting off the water ordinarily used to cool the exhaust and running the jackets at about 150° fahr., the jacket-water in circulating through the heater is raised to a temperature of 200° to 210° fahr., by the heat from the exhaust gases. This water may then be used for boiler feed or for heating buildings. By this method the actual heat efficiency of the gas-engine is increased from 25% to 68 %.

Discussion of J. R. Bibbins' Paper at Philadelphia.

January 11, 1904.

J. B. Klumpp:—The speaker is of the opinion that the author has not done justice to the gas-engine in that he has considered it principally in connection with a gas works, and not as a separate

proposition, operating with producer gas, which is the way that best results can be obtained from gas-engines. The gas-engine will probably, in the course of time, displace the steam-engine in many applications, although the increasing use of the steam-turbine, the internal-combustion engine of the Diesel type, and the possible introduction of a gas-turbine, must be held in view when this matter is considered. The character of the load for a gas works and an electric lighting plant is very different, in that the electric lighting plant has a short peak-load, while with the gas plant, only the total daily output need be considered. This daily output usually reaches a maximum in early winter, though sometimes the maximum is as great in September or October. The ratio of maximum to yearly output is frequently as high as 1/240 to 1/260.

If a gas-engine plant is to be used as an auxiliary to a gas works, the load of the gas-engines must be regarded in precisely the same light as an additional number of consumers, and a corresponding increase in the gas-making plant must be supplied. The maxima of the two loads will probably occur at the same time, and the engine cannot be regarded as using part of the output of apparatus that would otherwise be idle. The gas company must, for safe operation, hold a reserve capacity which should be available at the time of maximum daily output. In a few cases where a gas works has too great reserve capacity, it would be more economical to dispose of the surplus gas by the introduction of gas stoves for summer use, which would not be a tax upon the maximum daily output. If the proper increase is made in gas-making apparatus, there are few cases in which the total cost, including interest, depreciation, and repairs would be decreased.

Gas-engines using illuminating gas will probably never be introduced extensively, on account of the great cost of making this gas. Producer gas is undoubtedly the best for use with gas engines, except, of course, natural gas. With producer gas, the fuel cost can be reduced to from 0.35 to 0.5 cents per kilowatt-hour, which compares favorably with steam.

It is doubtful if gas-engines operating producers will give high efficiency at light loads, as the producers will either have to operate at a small fraction of their capacity, or the storage capacity provided be shut down for a time; hence the fuel consumption will not be reduced in proportion to the output. Moreover, the engines themselves at fractional loads, have a low efficiency. The cost of operation will be reduced both on account of lesser fuel cost and lesser attendance cost; but repairs on the engines will undoubtedly be greater than on a steam-engine.

The proposition to use the hot jacket-water for the heating system, would hardly be applicable beyond the engine-room itself.

[COMMUNICATED AFTER ADJOURNMENT.]

BY J. R. BIBBINS.

The author cannot agree with the speaker from Philadelphia that the gas-engine employed in conjunction with gas works for generating electric power represents an undesirable auxiliary and one that is incapable of securing to the gas works an all-day output of greater uniformity and consequently of less cost per unit. To be sure, with the usual electric light loads daily and yearly maxima for both gas and electric plants would nearly coincide, but it should be remembered that the electric plant affords an opportunity to work up an all-day factory motor-load which is ordinarily outside of the reach of the gas works. In any event, gas-storage capacity may be so readily provided, as compared with steam or electric storage, that the coincidence of gas and electric load maxima becomes a secondary consideration. On the other hand, a heating load is undesirable as it represents an idle investment through a large part of the year, and is incapable of control or limitation by contract to definite hours as in the case of electric-power load.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

NEW YORK, February 26, 1904.

The 184th meeting was held this date at the Chemists' Club, New York.

SECRETARY POPE:—At the meeting of the Board of Directors this afternoon, the following 62 Associates were elected:

Name.	Residence.	Endorsers.
ALLEN, CLAXTON EDMONDS,	Assistant Engineer General Electric Co.; res. 45 Hanover St., Lynn, Mass.	W. A. Hall. Elihu Thomson. E. E. Boyer.
APPLETON, JOSEPH,	Manager of Construction, Electric Storage Battery Co.; res. The Art Club, Philadelphia, Pa.	B. J. Arnold. C. T. Hutchinson. J. W. Lieb, Jr.
BERG, EDWIN VICTOR,	Draughtsman, Telluride Power Co., Provo, Utah.	H. J. Ryan. E. L. Nichols. Frederick Bedell.
BOTT, GEORGE ROBERT,	Chief Draughtsman, American Elevator Co.; res. 1083 Hunter Ave., Columbus, Ohio.	F. C. Caldwell. L. G. White. Perry Okey.
BOYD, ALEXANDER A.,	General Manager Michigan City Electric Co., Michigan City, Ind.	Abe Balsley. D. W. Roper C. W. Regester.
BRYANT, ARTHUR HORACE,	Tester Lamp Testing Bureau. 80th St. and East End Ave., New York, City.	W. S. Howell. F. M. Farmer. P. S. Millar.
COGGIN, WILLIAM LORD,	Tester General Electric Co.; res. 10 Arlington St., Lynn, Mass.	G. E. Sanford. E. E. Boyer. W. O. Bursch.
COPE, ALBERT NATHAN,	Electrical Engineer, Columbus Public Service Co.; res. 228 N. 21st St., Columbus, O.	F. C. Caldwell. M. C. Hull. Sheldon Roberts.
COSTA, LOUIS J.,	Manager, Jandus Electric Co., 1419 Real Estate Building; res. 5010 Newhall St., Philadelphia, Pa.	H. F. Sanville. C. W. Pike. Kern Dodge.
CRANKSHAW, J. B.,	Resident Engineer, Cincinnati Engineering and Investment Co., 1406 Traction Building, Cincinnati, O.	C. B. Humphrey. H. P. Davis. G. D. Shepardson.
CRANE, CHARLES EUGENE,	President and Manager, Mutual Light and Heat Co., Seattle, Wash.	K. G. Dunn. W. V. A. Sullivan. W. S. Wheeler.
DAVENPORT, ALFRED LA RUE,	Tester, Edison Electric Co. of Los Angeles; res. 1155 American Ave., Long Beach, Cal.	C. A. Copeland. J. G. Glassco. G. H. Gibson.

DAVIS, RICHMOND PEARSON, Instructor, School of Submarine Defense, Fort Totten, N. Y.	C. F. Parker. Eugene Griffin. Samuel Reber.
FENN, ERNEST JAMES, Partner, Steuart & Fenn, Dunedin, N. Z.	Frank Rich. William Steuart. R. W. Pope.
FLETCHER, RAYMOND FENNIMORE, Electrical Engineer McMaster and Fletcher, 338 E. State St., Columbus, O.	M. S. Browne. L. G. White. F. W. C. Bailey.
GRIFFIN, FRANK ALBEE, Engineer, General Electric Co., Schenectady, N. Y.	W. I. Slichter. J. E. Noeggerath. A. H. Armstrong.
GILLET, LOUIS ALLSTON, Assistant to Secretary, American Institute of Mechanical Engineers; res. 32 W. 10th St., New York City.	G. S. Dunn. J. M. Smith. G. F. Sever.
GRESHAM, WILLIAM ANDREW, Chief Dynamo Man, Georgia Electric Co.; res. 474 S. Pryor St., Atlanta, Ga.	Abe Balsley. R. W. Pope. J. N. Eley.
GRIFFIN, THOMAS LLOYD, Agent, General Electric Co., Wilkesbarre, Pa.	R. T. Lozier. E. P. Coles. Carl Hering.
HALE, WILLIAM BUELL, Laboratory Chief, Western Electric Co., 259 S. Clinton St., res. 6540 Lexington Ave., Chicago, Ill.	G. A. Damon B. J. Arnold. G. A. Hamilton.
HEDIN, KALEB, Electrical Engineer, Vesteras, Sweden.	E. J. Berg. R. W. Pope. W. G. Angus.
HILBERT, ALFRED, Draftsman, S.M. Bixby, 1173 Fulton Ave., Bronx, New York City.	W. A. Anthony. F. M. Hartmann. F. M. Farmer.
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And the following Associate was transferred to the grade of Member:

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THE CONDUCTIVITY OF THE ATMOSPHERE AT HIGH VOLTAGES.

BY HARRIS J. RYAN.

SYNOPSIS.

The present paper gives an analysis of the factors that are responsible for the nature of the atmospheric loss occurring on high-voltage lines as reported by Mr. Charles F. Scott in his paper that was published in the A.I.E.E. TRANSACTIONS, Vol. XV., p. 531, 1898, based upon results obtained by himself and those obtained by Mr. Ralph D. Mershon. The analysis shows that the equation

$$E_{max} = 2055 \log_{10}\left(\frac{s}{r}\right) D' (r+d) \times 10^{10} \qquad (10)$$

expresses the relation between the voltage, conductor sizes, and separation at which the sudden rise occurs in the curve of "loss between wires" at ordinary barometric pressures and temperatures wherein

E_{max} = the maximum value of the voltage-wave applied to the line.

r = the radius of the line conductor in inches.

s = the separation of the line conductors from center to center in inches.

d = the distance from the conductor surface at which the strain due to the electrostatic field causes initial atmospheric rupture.

D' = the strength of the electrostatic field of force (*dielectric flux-density*) that will electrically rupture the atmosphere at the distance d from the surface of the conductor having a radius r measured in coulombs per square inch.

To this is added an account of the experiments that were made to determine the above values of d and D' in relation to r and the effects due to barometric pressure and temperature changes and to the presence of moisture.

The values found for d and D' in relation to r at a barometric pressure of 29.5 inches of mercury and a temperature of 70° fahr. are given in the following table:

B. & S. G.	$2r$.	d.	D'.
20	0.03196	0.0050	350×10^{-10}
15	0.05706	0.0100	300×10^{-10}
10	0.10189	0.0180	275×10^{-10}
8	0.12849	0.0220	258×10^{-10}
6	0.16202	0.0350	200×10^{-10}
4	0.20431	0.0700	171×10^{-10}
2	0.25763	0.0700	170×10^{-10}
Measurements upon conductors of larger sizes to the limit of a diameter of 0.625 inch.	0.625	0.0700	170×10^{-10}

The experiments demonstrated that the voltage at which the atmospheric line loss is inaugurated varies as the atmospheric density; *i.e.*, directly as the barometric pressure and inversely as the absolute temperature. On substitution of corresponding values obtained by experiment, equation (10) takes the following practical form:

$$E_{max} = \frac{17.94b}{459. + t} \times 2055 \log_{10}\left(\frac{s}{r}\right) D' (r+d) \times 10^{10} \qquad (12)$$

wherein

b = the barometric pressure in inches of mercury.

t = the temperature in degrees Fahrenheit.

Since the values of d and D' are constant for diameters of conductors larger than 0.250 *inch*, it follows that equation (12) for corresponding conductors reduces to

$$E_{max} = \frac{17.94\, b}{459 + t} \times 350\,000 \log_{10}\left(\frac{s}{r}\right)(r + .07) \qquad (13)$$

The results obtained by calculation employing equations (12) and (13) are compared with the measurements made by Mershon on the Telluride high-altitude line in 1898 and those obtained by Professor Harold B. Smith upon the Worcester Polytechnic Institute laboratory line in 1901 and 1902 at ordinary altitudes.

Efforts were made to determine the effects of the presence of moisture upon the point at which the atmosphere about high-voltage lines becomes conductive, *i.e.*, upon the point at which the sudden rise in the loss-curve occurs. However, no definite effect of this sort could be found, and this is practically in accord with Mershon's conclusions after his observations made upon the Telluride line under variable weather conditions. If there is such an effect it must be small.

The following table of values has been calculated by means of equations (12) and (13). It shows the corresponding diameters of line conductors that must be employed to avoid loss between wires for a series of line voltages wherein the barometric pressure is 29.5 inches of mercury, the temperature 70° fahr., and the distance between the conductors 48 inches.

Maximum volts at which atmospheric conduction loss occurs.	Corresponding effective volts (sine wave)	Operating pressure, 90 per cent of corresponding effective volts.	Diameters of conductors in inches.
78 500	55 000	50 000	0.058
118 000	83 300	75 000	0.106
157 000	111 100	100 000	0.192
235 500	166 600	150 000	0.430
314 000	222 200	200 000	0.710
392 000	277 700	250 000	0.990

The real voltage limit to-day in transmission is due to the insulator, where the line has to be exposed to the weather. In the future the insulator difficulty will be solved in one way or another and higher voltages will be used. Possibly in large undertakings the line may be protected from the elements by means of a con-

tinuous covering. It is evident that when such high voltages are employed atmospheric conduction, or "the brush" (as one experienced high-voltage engineer termed it in conversation with the writer), must be avoided. High voltage brush discharge was studied and reported upon in the A.I.E.E. TRANSACTIONS by Dr. Steinmetz.* He applied to it the term *corona*. The present paper shows that the brush discharge or corona occurs always when a definite strain exists in the atmosphere next to the high-voltage conductors, and that to avoid such corona with its destructiveness and waste of power it is necessary on transmission lines and auxiliaries to proportion things so as to keep the dielectric strain of the atmosphere below a definite point above which the corona will inevitably develop.

In the above table a factor of safety of 1.11 or a margin of 10 per cent has been allowed in estimating the safe voltage at which to operate so as to avoid losses due to brush discharge. This is a laboratory conclusion only. In application the following points must be kept in mind:

1. Without special care there will be doubt in advance as to the exact value that the voltage wave will not exceed. Almost invariably the line-charging current will cause important line-voltage wave-distortion so that the maximum of the wave will exceed the effective value of the voltage by a factor much greater than the *square root of two*. The corona formation depends primarily upon the maximum and not upon the effective value of the wave; this has been found by Scott, Mershon and others, as well as in the present experiments.

2. One must remember that unless the insulators are properly proportioned, after the cross-arms and pins have been exposed to the weather for some time and have become conductive, the presence of the insulators made of material that has a considerably greater permeability to dielectric flux (greater specific inductive capacity) than the atmosphere, will cause corona to a greater or less degree to form over the conductors in their neighborhood, even if the line has been proportioned so as to avoid corona or atmospheric conduction over the remaining portion of the conductors. The presence of corona upon the conductors in the neighborhood of the insulators will likely be accompanied by corona over the pins inside the insulators, resulting in their

*TRANSACTIONS A.I.E.E., Vol. X, p. 85, 1893.

ultimate injury if made of wood from this cause alone, even if the surface leakage current is so limited as not to injure the pin.*

In view of the above it is evident that practical experience and not the laboratory must eventually determine the factor of safety that should be allowed under given circumstances in lieu of the 1.11 factor or the 10 per cent margin allowed in the above table.

The paper closes with the suggestion that when viewed in the dark the corona formed upon wires of given diameters and distances apart provides a method for gauging high voltages that is free from the short-circuit and surging disturbances occasioned by the use of the spark-discharge method. Either two parallel conductors or a conductor mounted at the center of a cylinder may be employed for this purpose.

Former Studies of Atmospheric Conduction.

The atmosphere is ordinarily the general medium in which electric circuits and apparatus are immersed. It is depended upon to a greater extent for insulation than any other medium or material.

Its dielectric strength to resist disruption by electric forces, in bulk, under ordinary conditions as to temperature, barometric pressure and entrained moisture, from an engineering point of view, has been the subject of extensive and critical investigation by Steinmetz, whose results have been communicated to the Institute in several papers.

Steinmetz found in his studies of the electric disruptive strength of the powerful solid dielectrics that the atmosphere surrounding the solid dielectric specimen and the electrodes applied thereto would break under the strain formed by the flux of electric force through it, much more readily than the solid dielectric. This gives rise to envelopes of conductive atmosphere located around the electrodes and over the surfaces of the powerful dielectrics. This phenomenon, which has the appearance of the familiar brush discharges so easily obtainable in electrostatic experiments was studied at some length and he applied to it the term *corona*.

Scott subsequently investigated experimentally the conditions under which the atmosphere in close proximity to high-voltage lines is subjected to electric stresses that bring it to the breaking point, causing the formation of brush discharges accompanied by losses of power in measurable amounts. Mershon,

*Burning of Wooden Pins on High-Tension Transmission Lines by C. C. Chesney, Transactions A.I.E.E., Vol. XX., p. 435, March 22, 1903.

independently of Scott, carried out a series of experiments at Telluride, Colorado, in which losses between wires due to high voltage were measured on a line 2.25 miles long, whereon the conductors having a diameter of 0.162 inch were mounted at various distances apart and between which pressures varying from 20 000 to 60 000 volts were applied. The results obtained through this series of investigations by Mershon and by Scott and his co-workers were reported by Scott to the INSTITUTE in a paper at the June meeting in 1898.

The characteristic phenomena of greatest interest to the engineer, as brought out in this classic paper, are those to which the Telluride curves of voltage and line-loss apply and which are charted in Fig. 6, Vol. XV., p. 545, as determined by Mershon and which for convenience is reproduced as Fig. 1 of the present paper.

The experimental and analytical study upon which this paper is based was undertaken for the purpose of securing further knowledge of the nature of the line-loss as observed by the above gentlemen.

THE ELECTROSTATIC FIELD.

When the terminal faces of a dielectric are in contact with conductors between which an electromotive force is applied, an electric force is exerted throughout the dielectric in variable degree, according to the position with reference to conductors. This electric force produces a distortion of the atomic structure of the dielectric; *i.e.*, a displacement of the electrons forming the dielectric atoms. Such electron-displacement, while in progress, constitutes an electric current. The displacement encounters the reaction due to internal atomic forces which tend to maintain the original structural form. This reaction is the cause of the formation of the familiar counter electromotive force of a condenser and is in proportion to the total amount of electricity or the time-integral of the current that was passed through the dielectric. When the process of atomic distortion proceeds beyond the point of structural rupture, the ordinary conduction-current ensues. Thus through a dielectric prior to the rupturing point the only current that can be passed is a *displacement current*. The passage of such displacement current and the establishment of the corresponding field of electrostatic force are merely cause and effect in one and the same operation. In any portion of the dielectric the value of the strength of the electrostatic field of force therein established is proportional to the

displacement of electricity, *i.e.*, to the time-integral of the displacement current that accompanied the establishment of such electrostatic field. For engineering purposes, therefore, the time-integral of displacement current may be conveniently employed as a measure of the strength of the corresponding electrostatic field of force.

The energy that is taken up in the formation of an electrostatic field of force per unit dielectric volume and which has been applied, therefore, in the passage of the corresponding time-integral of displacement current, is

$$J = \tfrac{1}{2} C E^2 \qquad (1)$$

where C is the capacity in farads; *i.e.*, the coulombs of displacement current per volt.

When an electromotive force of *one volt* is applied to the opposite faces of a centimetre-cube of air at ordinary barometric pressure and temperature, the energy taken up by the electrostatic field formed thereby throughout the cube, will be

$$441.7 \times 10^{-10} \textit{ joules}$$

No important change in this value occurs with variation of barometric pressure and temperature. When it is substituted in equation (1) the corresponding strength of electrostatic field thus produced per volt per centimetre of air expressed in coulombs of displacement current per square centimetre is found to be

$$C = 883.4 \times 10^{-10} \qquad (2)$$

For present convenience *strength of electrostatic field of force* will be referred to as *density of dielectric flux*. It may, therefore, be stated with reference to the dielectric permeability of air that,

One volt applied through a distance of one centimetre in air will establish a dielectric flux density of 883.4×10^{-10} *coulombs per square centimetre.*

This is the same thing as the capacity in farads of a condenser having surfaced electrodes of one square centimetre each, facing opposite sides of a centimetre cube of air.

In this method of designation it follows that the density of dielectric flux established per volt per unit area of conductor-terminal face is equal to the capacity in farads per unit area of such face. Thus in connection with a transmission line the total dielectric flux set up between conductors per unit length will be the product of the capacity of such unit length of line in farads and the applied electromotive force. The corresponding

density of dielectric flux extending from the surface of either conductor is the total flux per unit length divided by the corresponding conductor surface.

ANALYTICAL STUDY OF MERSHON'S RESULTS.

From the work of Steinmetz it is known that

a. The atmosphere and the gases generally, conduct after disruption in two forms:

1. Arcs or very hot streamers. A concentrated conduction at high current-density.

2. Corona or brush discharge. A diffused conduction at low current-density, developing heat at lower intensity.

b. 1. The dielectric strength of the atmosphere in bulk is such as to require for rupture approximately a pressure-gradient of 10 000 sine wave effective volts per inch.

2. The thin zones of atmosphere that enclose the electrode and which are in immediate contact therewith have a far greater dielectric strength than air in bulk, corresponding to a ratio of dielectric strengths of from five to ten.

From the nature of sparking discharges through air the conclusion is reasonable that whenever the flux of electric force, or more briefly the dielectric flux, through the air in a given state as to temperature, pressure, and freedom from foreign material, rises to a certain value an atomic structural rupture of the air will occur, resulting in conduction.

From Steinmetz's results it is evident that this maximum value of dielectric flux-density at which atmospheric disruption will not occur will depend upon the position of the particular portion of the atmosphere being considered relative to the conductors or electrodes between which the high voltage is applied.

The classic electrostatic experiments as well as the modern Paschen's law,* which has been tested to above five atmospheres and which asserts that the sparking discharge voltage through given distances in air increases with the atmospheric density and, therefore, as the pressure and inversely as the temperature on the absolute scale, make it reasonable to conclude that the minimum dielectric flux density that will cause atmospheric conduction will vary as the atmospheric density and therefore directly as the barometric pressure and inversely as the temperature on the absolute scale.

*Conductivity of Electricity through Gases. J. J Thomson, Edition of 1903, p. 367.

The researches of Hittorf, Crooks, J. J. Thomson and others, including some recent work upon this particular point by Dr. Blaker, make it reasonable to conclude that so far as concerns magnitudes which are appreciable in engineering, the atmosphere under ordinary conditions and fairly clean, *i.e.*, free from floating

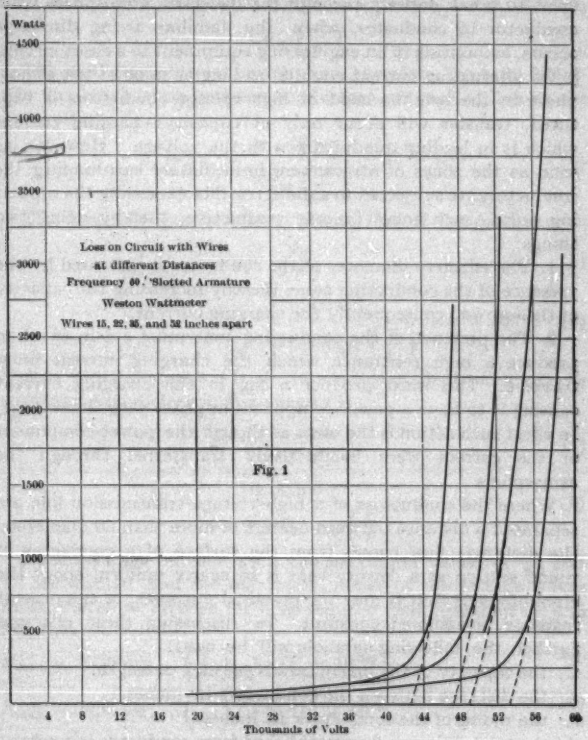


FIG. 1.

conducting material, will not conduct appreciably in the neighborhood of high voltage lines when their surfaces are bare, so long as no portion of such atmosphere is permeated with a dielectric flux that is not sufficient to cause rupture at any one point.

When the dielectric flux exceeds the rupturing point, conductivity ensues and there is a conductive transfer of current from conductor to conductor through the atmosphere.

On continuous-current circuits the amount of transfer of such current must be small prior to the application of a voltage sufficient to break entirely through the dielectric atmosphere from conductor to conductor, when the familiar arcing discharge occurs, amounting in an engineering equipment to a short-circuit.

On alternating-current circuits, as long as none of the atmosphere in the neighborhood of high-voltage conductors is ruptured, transfer will occur only of capacity charging current which is in leading quadrature with the voltage. However, as soon as the zones of atmosphere immediately surrounding the conductors are subjected to a dielectric flux exceeding the rupturing point, such zones become conductive, thereby doing two things:

1. The effective diameter of the conductor is increased by the presence of the conducting zone, thereby increasing the capacity of the line and consequently the charging current.

2. The presence of the conducting zone must act in effect to produce a high resistance which the charging current must traverse. This must produce a lag in the charging current causing it to have a power-component in phase with the voltage. In effect such action is the same as though the power-component of the current were conductively transferred through the atmosphere.

Where the conductors of a high-voltage transmission line are separated a distance between centers of more than 20 diameters, the dielectric flux passes from the surface of a conductor of round section at a density that is so nearly uniform about the circumference that it may for practical purposes, in the present instance, be assumed constant. In discussing these relations further the following symbols will be used:

C, the capacity of the line in farads per inch of length.

s, the distance between the conductors in inches.

r, the radius of the conductors in inches.

ϕ_o, the total dielectric flux established from conductor to conductor, measured in terms of the corresponding displacement current; *i.e.*, in coulombs.

D_o, the dielectric flux-density at the surface of the conductor in coulombs per square inch of sectional area.

D', the corresponding dielectric flux-density at a distance slightly remote from the surface of the conductor, where the

extraordinary dielectric strength of the atmospheric zone ceases and where occurs the region of greatest dielectric strain relative to the disruptive strength.

D, the corresponding dielectric flux density at any point.

The capacity between wires in farads per inch of line is

$$C = \frac{0.00306}{\log_{10}\left(\frac{s}{r}\right)} \times 10^{-10}* \qquad (3)$$

The total displacement current and, therefore, the total dielectric flux established between conductors per inch of line at the line voltage, E, is

$$\phi_0 = EC = \frac{0.00306}{\log_{10}\left(\frac{s}{r}\right)} \times E \times 10^{-10} \qquad (4)$$

The dielectric flux density at the surface of the conductor is

$$D_0 = \frac{\phi_0}{2\pi r} \qquad (5)$$

$$D_0 = \frac{0.00306}{2\pi r \log_{10}\left(\frac{s}{r}\right)} \times E \times 10^{-10} \qquad (6)$$

At a radial distance d from the surface of the conductor, the corresponding dielectric flux density is

$$D' = \frac{\phi_0}{2\pi (r+d)} \qquad (7)$$

$$D' = \frac{0.00306}{2\pi (r+d) \log_{10}\left(\frac{s}{r}\right)} \times E \times 10^{-10} \qquad (8)$$

In alternating-current work the maximum values of D_0 and D' are wanted, and the maximum values of the voltage waves must, therefore, be used for E, as reduced from equations (7) and (8), thus:

$$E_{max} = 2055 \log_{10}\left(\frac{s}{r}\right) . r . D_0 \times 10^{-10} \qquad (9)$$

$$E_{max} = 2055 \log_{10}\left(\frac{s}{r}\right) (+d) D' \times 10^{-10} \qquad (10)$$

When Mershon's results given in Fig. 1 were used to test these equations it was found that they correctly accounted for the relation between the separation of the conductors and the voltage at which the initial brush discharge took place. These results gave also a certain value for D_0 which would not give correct

*Perrine and Baum, TRANS., A. I. E. E., Vol. XVII., p. 352, May 18, 1900.

results when used to determine the voltage required to start the line loss for the small wires used by Scott in some of his experiments at Pittsburg.

At this point a rough laboratory test was made to see whether one would find the start of the loss between wires to occur at the same voltages for the same size of conductor and distances apart

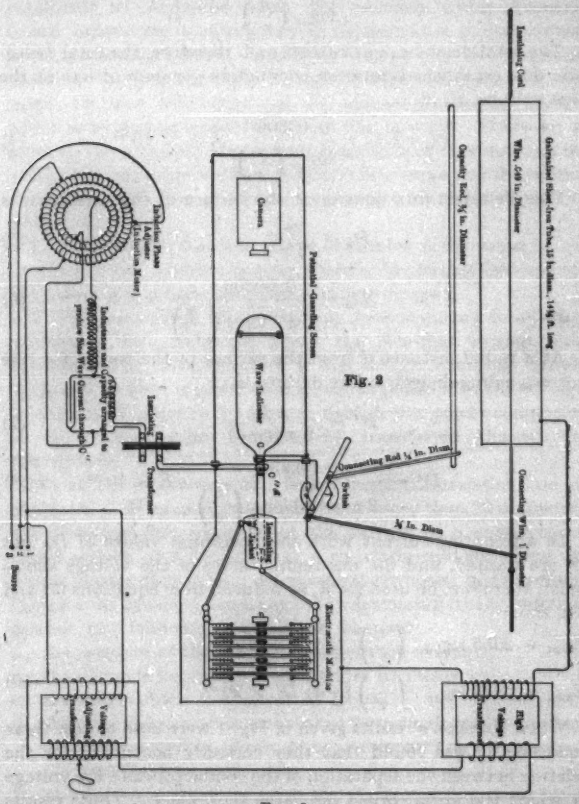


FIG. 2.

that Mershon found. The results obtained were totally different. It became evident from this disagreement that barometric and

temperature variations exerted important influences. The difference between the approximate results obtained by the author and those of Mershon indicated that the voltage starting the loss between wires would vary as the barometric pressure. When, however, the values deduced from the Telluride results were correspondingly corrected for barometric pressure and applied as constants in these equations the voltages observed by Scott for starting the loss on small wires were in no wise predicted. Upon thinking over the probable causes for this, it seemed that the reasons were most likely as follows:

The dielectrically powerful atmospheric film surrounding the small wire would cause the initial rupture to occur at a distance from the surface of the conductor entirely appreciable with respect to the radius of the conductor, in which event some value of D' different from D_0 would be responsible for the initial rupture of the atmosphere. The value of D' would be indeterminate so long as we have no means for determining the distance from the surface of the conductor at which the initial rupture occurs. Again, it was apparent that the values of D' and the distances at which they occur from the surface of the conductor might vary in an unknown manner relative to the radius of curvature of the conductor.

It became evident that a series of experiments would be necessary in order to obtain all of the data required to write properly the formulas expressing the relation of all the factors that control the start of the atmospheric loss between wires.

It was determined first of all to check by experiment the impression gained from the observations of Scott that the visual appearance of the corona or brush discharge on the wire occurs simultaneously with the initial formation of energy-loss, as the line voltage is raised; and to observe the nature of the charging current with respect to the line-voltage with a view to determining more data regarding the origin of the loss. Should the start of the loss be accompanied simultaneously by the visual appearance of the corona over the wire, this would be an easily discernible fact that would greatly facilitate subsequent experimental work. The point at which the atmospheric conduction-loss would occur in relation to diameters of conductors, their distance apart, applied voltage, barometric pressure, temperature, moisture, and the thickness of the dielectrically powerful but thin zones of atmosphere could then be noted simply by watching for the appearance of the corona.

For this purpose it was realized that the most convenient and effective laboratory arrangement of the line would be to suspend a single wire for observation at the center of a metallic tube of suitable diameter much the same as originally suggested by Mershon. There are three evident advantages which this arrangement has in laboratory work of this character over the use of a pair of parallel wires.

1. The dielectric flux established about the wire between it and the cylinder is easily and exactly estimated in terms of the dimensions of the wire and cylinder and the dielectric flux-constant or specific inductive capacity of the atmosphere. The flux emanates uniformly from the wire, thus making definite the results deduced from observations.

FIG. 3.

2. A lower voltage suffices to cover a given range of experimental study.

3. The tube may easily be made to contain atmosphere at various pressures, temperatures, and degrees of entrained moisture.

At this stage of the work in April, 1903, Mr. H. C. Ford, a senior student in my classes, assisted by Mr. C. L. Wernicke undertook as a thesis to make the experiments. The author is greatly indebted to these young men for the energetic and effective manner in which they did the work.

They erected apparatus, determined and charted results as follows:

The general plan for observing the details of the corona and loss phenomena due to high voltages with the aid of a cathode-ray wave indicator is given in Fig. 2. A brass wire 0.049 inch in diameter was mounted at the center of a galvanized sheet iron tube 15 inches in diameter and 14.5 feet long, as shown. Between this wire and the tube high pressure was applied and adjusted to any desired value up to 80 000 effective volts by means of the transformers as shown.

The arrangement permitted the coils C' of the wave indicator to be inserted by means of a switch, as shown, in series with the

FIG. 4.

wire so as to indicate whenever desired the charging current set up from the wire to the cylinder. In order to note at a glance any departure of the wire charging-current the charging-current form that should exist if no atmospheric conduction were present, a 0.75 inch brass rod with well-rounded ends was placed outside the cylinder and connected through the switch to the same terminal of the transformer as the wire. The arrangement was such as to permit quickly the switching of the indicator coil C', in series either with the wire or rod Then at low voltages prior to the disruption of the atmosphere about the wire, the indicator

diagram produced by the wire and rod-charging currents were adjusted to equality by moving the rod in its position relative to the cylinder.

A-sine wave current controlled by a proper circuit of inductances and capacity and passed through C'', produced the known indicator motion.

In the use of high voltages in this manner two precautions must be taken in the use of the wave indicator. It must be entirely enclosed in a potential-guarding screen set up on high-voltage insulators and a connection must be made from the screen to

FIG. 5

the terminal of the transformer that is connected to the wire and capacity-rod. The sine-wave current must pass through an insulating transformer and the secondary must be connected to the guard screen so as to protect the low-voltage source and relieve the indicator of electric stress at all points.

A three-phase source was employed so as to draw for convenience the sine-wave current through an induction phase adjuster as shown. By shifting the sine wave, any intricate part of the unknown wave was made to occur when the sine wave was pass-

ing through zero and, therefore, changing most rapidly, thus unfolding the intricate portion of the unknown wave so as to be observed and recorded to best advantage.

Figs. 3, 4, 5, and 6 are half-tone reproductions of diagrams of line-wire and capacity-rod charging currents, photographed from the screen of the indicator. Eight of these were observed

FIG. 6.

in this series at maximum voltage wave values varying from 23 000 to 48 000 volts. To give a clear idea of the characteristics of these diagrams it is necessary to reproduce only the above four.

In Figs. 3′, 4′, 5′ and 6′ the waves indicated in Figs. 3, 4, 5 and 6 are drawn to scale in rectangular coördinates. They show at once the nature of the phenomena of atmospheric conduction

giving rise to a loss between wires at high alternating voltages.

The waves of line and condenser charging currents are identical in Figs. 3 and 3′, which were observed at a voltage having a maximum value of 23 000. The voltage was not yet high enough to cause the atmosphere about the line-wire to break and become conductive. The charging current applied from the wire to the cylinder was identical with the true capacity charging-current from the rod to the cylinder.

When the voltage was slightly raised, a well-defined though small change in the line charging current appeared as a hump on either side of its indicator diagram, (see Fig. 4), or a sudden increase in the current, just as it was about to pass through zero, as seen in the rectangular coördinate diagram of this same wave shown in Fig. 4′.

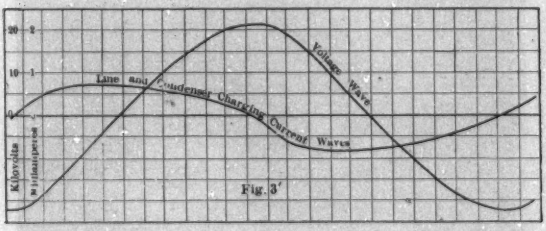


FIG. 3′.

At exactly the same value of voltage at which this hump in the line-current appeared the corona became visible when viewed in the dark, thus settling definitely this point and providing a convenient and reliable guide in subsequent experimental studies.

It should be observed that the manner of departure from normal capacity-form of the line charging current is much as one would expect from prior knowledge. After the phenomenon has been started, at that instant in each cycle when the voltage attains a value of 20 000, the atmosphere about the line-wire breaks and forms a conducting envelope about the wire. As the value of the voltage is very near the maximum it follows that the disrupting dielectric strain can last but a brief portion of a cycle. Beyond this the normal true capacity condition will be resumed in which the rod and wire charging currents are again

in agreement. The atmospheric conducting action in this instance, then, is to increase the capacity of the wire by covering it with a high resistance conducting envelope during that portion of the cycle in which the instantaneous voltage is high enough to maintain in the atmosphere next to the line-conductor a state of strain sufficient to maintain disruption.

Thus it is seen that the electric circuit from the wire to the cylinder changes during the cycle from a state of true and unvarying capacity to one of increased and variable capacity in series with a high resistance.

These two actions evidently contribute to the same result; viz., the establishment of a component of current passing from wire to cylinder that is in phase with the voltage and which, therefore, dissipates energy in heat at a corresponding rate.

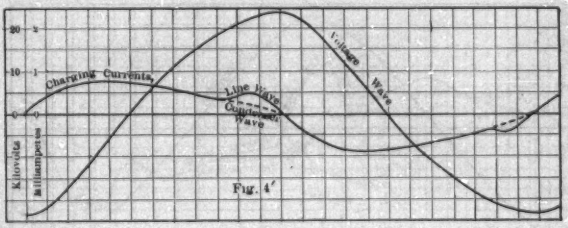


FIG. 4'.

We did not succeed in starting the hump in the line-current wave at a lower voltage than that applied for Figs. 4 or 4'. By raising and lowering the voltage and watching the indicator it was evident that it required a slightly higher instantaneous voltage to start the conduction than that required to maintain it. It is highly probable that the high temperature reached by the conducting envelope, due to heat produced by the current, will account fully for this.

As the voltage is raised the departure of the line charging-current from its normal true capacity form occurs to a remarkable degree. The maximum value of the voltage-wave was set at 26 500 volts and the card of Fig. 5 was obtained from which the waves of Fig. 5' were determined. Qualitatively, there are here observed precisely the same phenomena as in Figs. 4 or 4'. The atmosphere remains conductive during a large part of the cycle.

returning to the normal with corresponding coincidence between the condenser and line currents during the remaining small portion of the cycle. It may be noted that whereas 20 000 instantaneous volts were required to maintain a minimum corona in the condition that produced Figs. 5 and 5′, the definitely lower value of 17 000 volts is required due again probably to the higher temperature of the ruptured atmosphere.

When the voltage wave was raised to the maximum value of 48 000 volts, the cards and corresponding waves in Fig. 6 and 6′ were obtained, while the disruption evidently occurs at 17 000 volts as before. So important a part is now taken by the resistance and fluctuating capacity that there is no longer a continuation at any point throughout the cycle of coincidence between the capacity rod and line-wire charging currents.

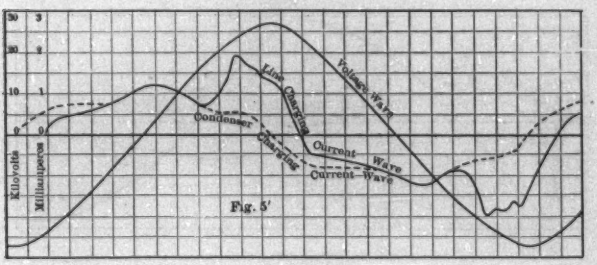


FIG. 5′.

These voltage-waves were determined by integrating the capacity rod charging currents. Their scale was obtained by observing the maximum values by means of a spark-gap. The wave-indicator scale for the currents in the case of each card was easily obtained from the effective value of the sine-wave current read from an ammeter connected in circuit with the coil C''.

In all, eight of these cards were taken and worked up in the foregoing manner. Products of the current and voltage waves were made and averaged by integration so as to obtain the watts lost in corona display over the wire at each corresponding alternating voltage applied. These results were charted in Fig. 7, locating the curve there drawn.

The way was now clear to determine experimentally the validity of the expression derived above, provided there was

some method for determining the distance from the surface of the conductor at which the initial break occurs. I am indebted to Mr. B. T. McCormick, a senior student in my classes last year, for a method by means of which this may be accomplished. Assisted by Mr. C. L. Gillespie he applied it to many of the commercial sizes of conductors ranging in diameters from 2 to 625 mils. At the center of the 15-inch cylinder conductors of various diameters were mounted. An alternating voltage was applied

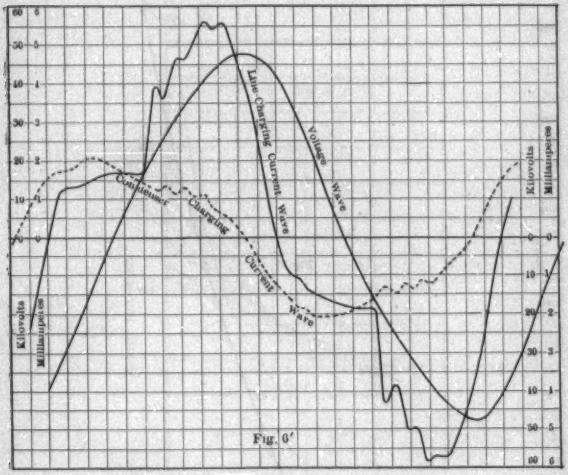


Fig. 6'.

between the conductor and the cylinder and elevated to the point at which corona is first visible in the dark. The diameter of the conductors and the maximum value of the voltage waves were observed by means of the spark-gap. Corresponding to each conductor and the maximum value of the voltage at which its corona was initially formed, curves were located showing the relation between the dielectric flux-density and radial distance from the surface of the conductor. These curves were then plotted in rectangular coördinates in the

same manner as shown in Fig. 8. The envelope of these curves when taken at sufficiently small intervals of conductor sizes, gives the relation between the distance from the surface of the con-

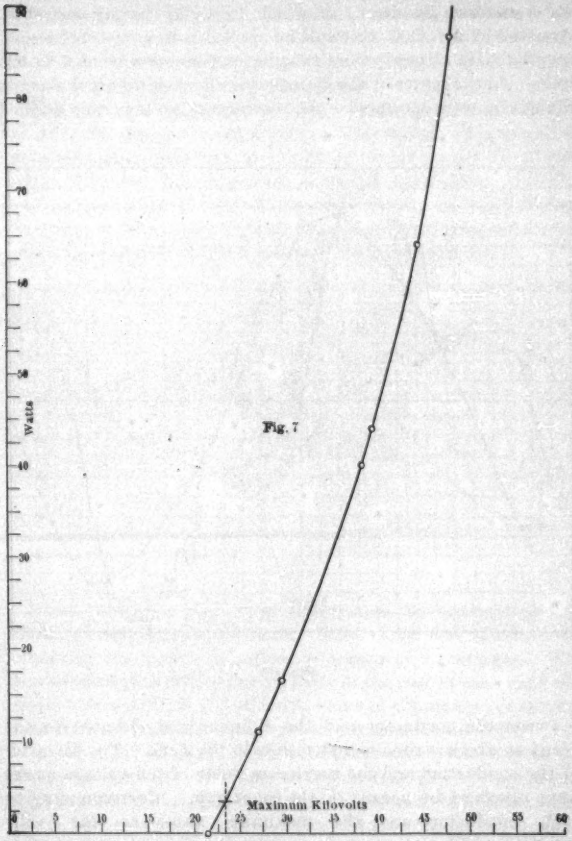


Fig. 7.

FIG. 7.

ductor and the dielectric flux-density at which the atmosphere first ruptured. In this manner the relation between the conductor-diameter, distance from surface and dielectric flux rup-

turing density, was determined. The values thus determined are given in the Synopsis; *i.e.*, in the tables on page 4.

One especially interesting feature of the results given in this table is that the distance from the surface of the conductor at

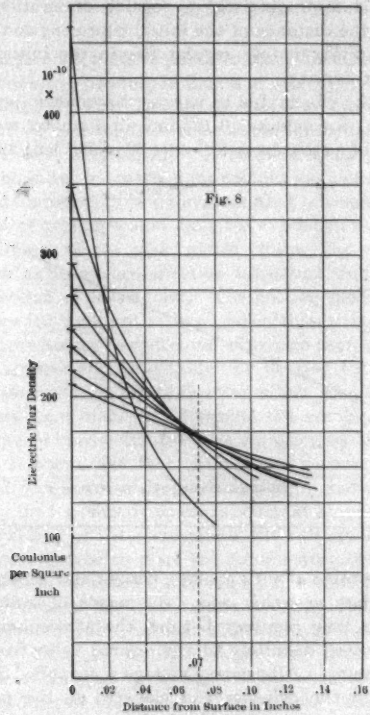


FIG. 8.

which the atmosphere first ruptures is constant at 0.07 inch. for all diameters above 0.25 inch and the corresponding rupturing flux value is constant at 170×10^{-10} coulombs per square inch. The largest conductor used in these experiments was 0.625 inch

in diameter. It is, however, reasonable to expect that since there is no change in the value of d due to changes in the conductor-curvature when the diameter varies from 0.25 to 0.625 inch, there will be no important change in such value of d for conductors of larger diameters. At conductor-diameters smaller than 0.25 inch, there is approximately a regular diminution with the diameter, of the distance of the initial rupturing-zone and a corresponding approximately regular rise in the initial rupturing dielectric flux-density.

To study the effects due to varying barometric pressures and temperatures, a conductor 0.125 inch in diameter was mounted at the center of a stout brass cylinder 20 inches long and 8.75 inch

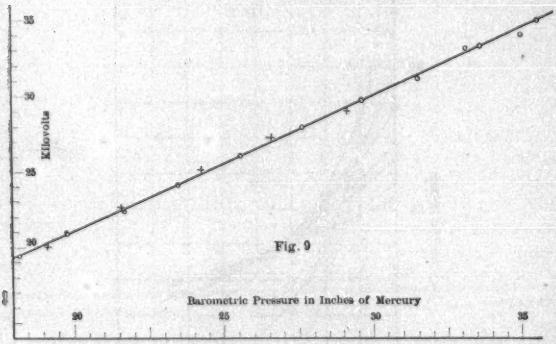


Fig. 9

in diameter, provided with packing flanges and closed with 0.5 inch plate-glass at either end. By means of ordinary hand-pumps and a long mercury U-tube, the atmospheric pressure could be adjusted definitely to any desired value from 18 to 36 inches of mercury. Alternating voltage was applied between the conductor and the cylinder and elevated to the point where the corona was observed in the dark to appear suddenly. The effective values of the voltage were determined by means of a Weston alternating-current voltmeter applied across the terminals of the low-voltage primary of the high-voltage transformer. Throughout all experiments the form of the voltage-waves was approximately the same; viz., that given in Figs. 3′ 4′, 5′ and 6′; frequency 130 cycles.

With the atmosphere in the cylinder at the room-temperature of 70° fahr., the observations showing the relation between corona starting-voltage and atmospheric pressure were made that are found charted in Fig. 9. They locate a right-line relation, the equation of which is

$$K_v = 0.902\, b + 2.93 \qquad (11)$$

wherein

K_v = effective kilovolts required to start the corona.

b = barometric pressure in inches of mercury.

To determine the effect of variation of temperature upon the voltage required to inaugurate the corona, the air in the tube was heated electrically and cooled by immersion in a salted ice-pack. However, the salted ice method for cooling was not a success and had to be abandoned, it being evident that a much more extensive method of cooling would have to be used in order to maintain the surfaces of the glass plates closing the tube free of moisture, so as to ensure effective insulation and clear vision for the detection of the corona. The cooling facilities that are evidently needed were not at hand when these tests were made, last May, so we had to be contented with such temperature variation of the air as could be obtained by heating the tube electrically by means of a jacket of German-silver wire and asbestos. Observations were made to determine the combined effects of temperature and barometric pressure variation by heating the air in the tube to about 200° fahr., at a given barometric pressure, then as the temperature dropped slowly by radiation and by maintaining the barometric pressure constant by use of the pump or by natural flow of the atmosphere, the voltage at the various temperatures required to start the corona were observed. The process was then repeated for another barometric pressure until finally observations had been made covering the temperature range of from 70° fahr., to near 200° fahr., at barometric pressures ranging from 19 to 34 inches. The humidity present was that due to natural causes and was not observed.

A target-diagram of these observations, including those made at 70° fahr., is shown in Fig. 10. The observations made at room-temperature are much more reliable than those made at other temperatures. The reason for this is the uncertainty of the actual temperature of the atmosphere in contact with the conductor at the center of the tube when at a different temperature from that of the outside atmosphere. The difference in temperature causes a transfer of heat from one side to the other

that occurs largely by means of convection currents that give rise to the uncertainty of the temperature at the center of the tube. However, the observations made at the constant barometric pressures of 29, 26.5 and 19 inches of mercury left no doubt of the nature of the barometer temperature-voltage variation as shown by the lines thus located in Fig, 10 and which indicate a close agreement between the variation of the corona-forming voltages and the atmospheric density.

The fact that there is an addition-constant in the equation for the barometric pressure-kilovolt line for 70° fahr., in equation (11) shows that the barometric pressure-temperature-corona-forming voltage relation of Fig. 10, will not be accurately expressed in a formula which assumes that the corona-forming voltage varies

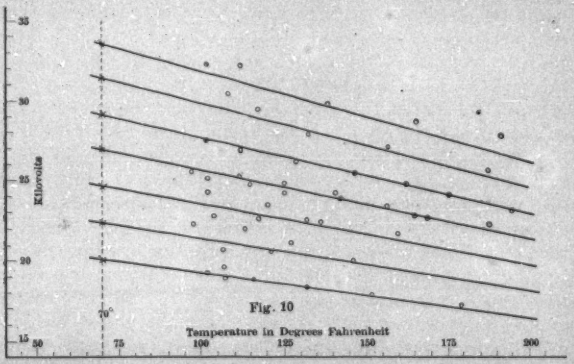


Fig. 10

The constant barometric pressures at which the lines in this diagram were located are, beginning at the top : 34, 31.5, 29, 26.5, 24, 21.5, and 19 inches of mercury.

exactly as the density of the atmosphere. However upon trial it was found that the assumption that it does so vary will provide an expression giving the results charted in Fig. 10 with sufficient accuracy for practical purposes.

The corresponding correction-factor to be applied to equation (9), to account for barometric pressure effects different from 29.5 inches of mercury and temperatures different from 70° is

$$\frac{17.94\,b}{459+t}$$

wherein

b i. the barometric pressure in inches, and

t th. temperature in degrees on the Fahrenheit scale.

The final equation which allows for all important factors showing the relation between the instantaneous maximum voltage, size, and separation of conductors, rupturing value of dielectric flux, and distance from the surface of the conductor at which the rupture occurs, causing initial corona formation should, therefore, be written

$$E_{max} = \frac{17.94\, b}{459+t} \times 2055 \log_{10}\left(\frac{s}{r}\right) D' (r+d) \times 10^{-10} \qquad (12)$$

A determined effort was made to observe the effect upon the point of initial corona formation due to the presence of moisture in the atmosphere. The ordinary air in the tube was displaced with dry air and the corona-starting voltage was then observed. Steam was then admitted to the interior of the cylinder and after allowing sufficient time for the water that was not absorbed by the air to settle upon the walls of the cylinder, the corona voltage was again observed. By this method the effect of the presence of humidity could not with certainty be detected, leading one to conclude that such effect if it does exist is small.

Where the conductors are 0.25 inch or larger in diameter, D' and d remain uniform at

$$D' = 170 \times 10^{-10}, \textit{ coulombs per sq. in.}, \text{ and}$$
$$d = 0.07 \textit{ inch}$$

and equation No. (12) becomes

$$E_{max} = \frac{17.94\, b}{459+t} \times 350\,000 \log_{10}\left(\frac{s}{r}\right) (r+.07) \qquad (13)$$

The data for Mershon's experimental line are

s = 15, 22, 35, and 52 inches.
r = 0.081 inch.
D' = 200×10^{-10} coulombs per sq. in.
d = 0.035, inch.
t = about 60° fahr.
b = about 20 in.
1.71 = approximate ratio of maximum to effective value of voltage wave.

Upon substituting these values in equation (12), the following results are obtained.

Separation of Lines.	Effective Voltage at which Initial Corona Loss Occurs.	Mershon's Observations. Effective Voltage.
Inche .		
15	43 600	43 500
22	4 800	47 000
35	50 700	49 000
52	54 000	53 500

In this table the values labelled "Mershon's Observations" were taken at the point of intersection of the voltage base-line in Fig. 1 formed by the broken-line extension of the vertical portion of the loss-curves. Mershon's conclusion is that the small loss portion, *i.e.*, the horizontal portion of these loss-curves, is due to the line insulators while the large increase of loss beyond the sharp rise in the curve is due only to the atmospheric loss. The laboratory tests confirm this fully. Some will insist that if this is strictly so the sudden rise in the loss-curve should make an abrupt and not a gradual turn upwards. Upon further thought it must be evident, however, that as the voltage is raised atmospheric conduction will first appear over the sections of the wire in contact with the insulators which have a higher specific inductive capacity, *i.e.*, a higher permeability to dielectric flux than the atmosphere, causing the electrostatic field about the wire in the neighborhood of the insulators to be higher than in a position remote therefrom. On this account the initial start of the atmospheric conduction-loss will not appear abruptly when the voltage is increased gradually through the corona-forming value. It is to be noted that the vertical portions of these loss-curves as extended to the base of the diagram, form curves having substantially the same character as the corresponding laboratory loss-curve given in Fig. 7. It is from this point of view that the above method was employed for locating the value of the voltages that started the corona losses on the Telluride line.

Professor Harold B. Smith has erected an experimental high-voltage line at Worcester Polytechnic Institute, 250 feet long, upon which conductors have been mounted varying in size from No. 10 to No. 2 B. & S. G. and high-voltage losses have been measured, due to electromotive forces ranging from low values to

upwards of 250 000 volts. He has very kindly given me three of his voltage-line-loss curves taken from these lines, arranged as follows:

Length of lines, 250 feet. Observed May 14, 1901; May 3 and 28, 1902. Barometric pressure 29.5 inches; temperature, 70° fahr.

Curve No. 1. Size of wire No. 10 B. & S. gauge. Separation 30 inches, voltage-line losses measured over a range from 30 000 to 100 000 volts.

Curve No. 2. Size of wire No. 2, B. & S. gauge., separation 24 inches, voltage-line losses measured over a range from 30 000 to 145 000 volts.

Curve No. 3. Size of wire, No. 2 B. & S. gauge., separation 48 inches, voltage-line losses observed over a range from 30 000 to 150 000 volts.

For a No. 10 B. & S. gauge wire:

$$d = 0.018 \text{ inch.}$$
$$r = 0.05095 \text{ inch.}$$
$$D' = 275 \times 10^{-10}.$$

No. 2 B. & S. gauge wire,

$$d = 0.07 \text{ inch.}$$
$$r = 0.1288 \text{ inch.}$$
$$D' = 170 \times 10^{-10}.$$

Substituting numerical values in equation (13) for the two No. 2 lines and in (12) for the No. 10 line, the following results are obtained for comparison with the measurements by Smith. (See table on page 304.)

Smith's voltage-measurements were made with a special and highly satisfactory form of electrometer. Strict agreement of the calculated and effective results cannot, however, be expected without a knowledge of the ratio of the maximum to the effective values of the actual high-voltage waves impressed upon the line. The last column in the above table gives these corresponding maximum effective ratios that would bring the calculated and experimental results into exact agreement. The ratios indicate the use of a somewhat peaked line-voltage wave which is apt to be the case owing to the distortion produced in the high-pressure transformer by the delivery of the line charging-current.

Naturally the conductor having a circular exterior section is the one best adapted, other things being equal, for the avoidance of atmospheric loss. The ordinary stranded cable exposes nearly a circular sectional area, so that in respect to the avoidance of this sort of loss the cable should give substantially the same

results as the solid conductor. Evidently when the voltage is such as to demand a greater exterior diameter of conductor than that corresponding to the solid section required for the economical or efficient transmission of the current, the solid or stranded

Line.	$E_{max.}$ Maximum instantaneous voltage at which corona loss occurs, determined by equations (12) or (13).	$E_{ff.}$ Reduced from $E_{max.}$ by the factor $\sqrt{2} = 1.415$	$E_{ff.}$ Observed by Smith. (Located by intercept upon voltage axis of voltage-watt curve as was done in connection with Mershon's curves, Fig. .)	$\frac{E_{max.}}{E_{ff.}}$ As a factor in lieu of $\sqrt{2}$ required to bring calculated and observed results into exact agreement.
No. 10 B. & S. G. 30 in. separation.	107 700	76 000	66 000	1.63
No. 2 B. & S. G. 24 in. separation.	158 000	112 000	100 000	1.58
No. 2 B. & S. G. 48 in. separation.	178 500	126 000	110 000	1.61

conductor can be made hollow or provided with a non-conducting core. A few observations were made by using round, hexagonal, and square conductors at the center of a 15-inch cylinder for the

purpose of obtaining comparative data, applicable to the corona-forming voltage as affected by those forms of sections. These observations are charted in Fig. 11, from which it is seen that while the exterior surface and total section of the hexagonal conductors are greater than for the same thicknesses of round conductor, yet the corona-losses are started at lower voltages. The same is true naturally to a greater extent for the square conductor. The cause of this is obviously due to the concentration of the dielectric flux at the surface-angles of the non-circular sectioned rods.

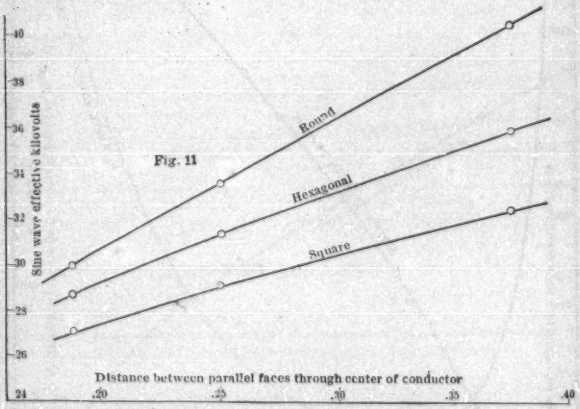


Fig. 11

The curves in Figs. 12 and 13 were determined from observations made in the thesis work of Ford and Wernicke, and McCormick and Gillespie. They are reproduced here because they constitute original data that are useful for analogous purposes other than those to which they were applied in this paper. The curves labelled "Sine Wave Effective Kilovolts" give the relation between the voltages and diameters of conductors mounted at the center of the 15-inch cylinder at which initial corona occurred for a diameter range of 3 to 600 mils. The remaining curves give the corresponding calculated dielectric flux-densities at the conductor surfaces. The voltages were determined by a spark-gap discharger having a scale laid off in terms of sine wave effective volts.

A Substitute for the Spark-gap Method for Gauging the Mamixum Values of High Voltages.

The maximums of the highest alternating voltage-waves may

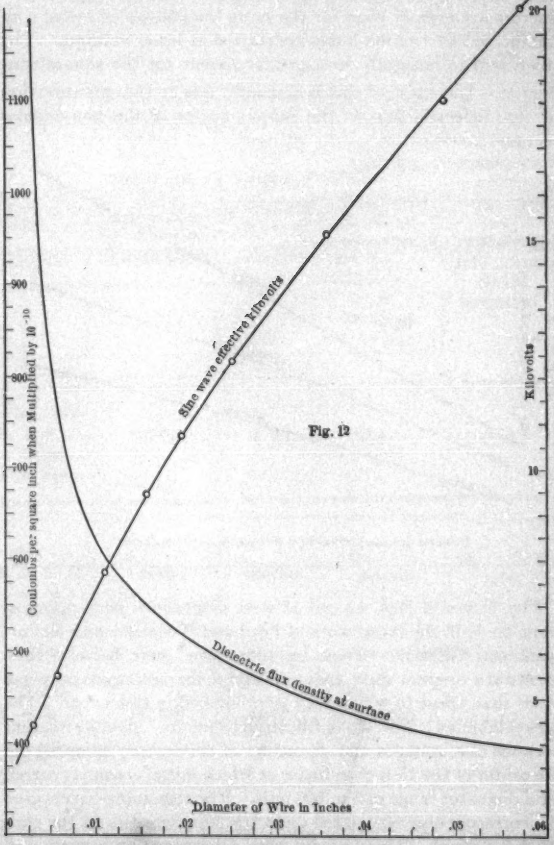
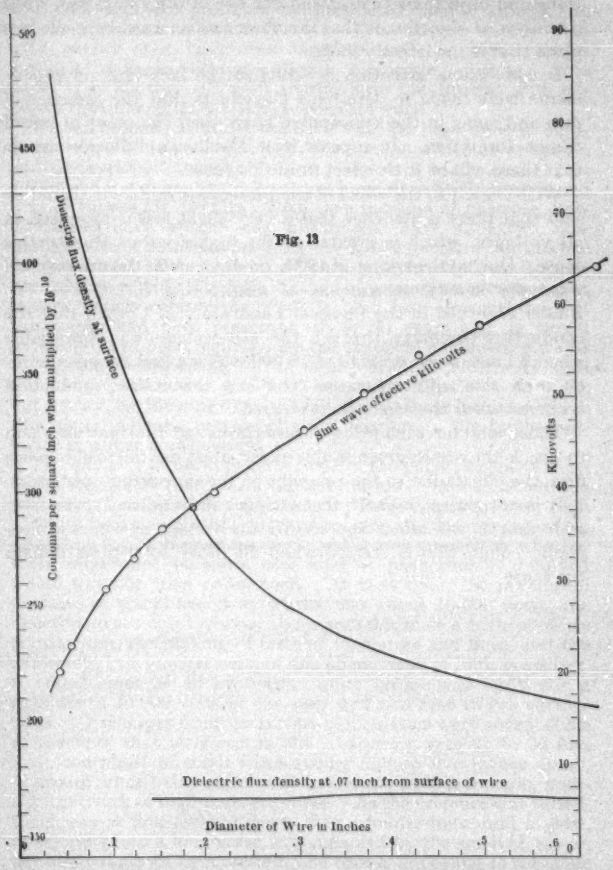


Fig. 12

be gauged easily when applied between wires of suitable diameter the separation of which is adjusted until the initial corona appears

in the dark. From the conductor diameter and separation, barometric pressure and temperature, a determination of the



maximum of the voltage-wave may easily be made that will be just as accurate as the constants in the equation (10), or the location of the curves in Figs. 12 and 13, or made with such

increased accuracy as will be obtained in similar determinations in the future. This method is free from the fluctuating indications and objections that attend the use of the spark-gap, while its only real objection is that the observations must be made in a place that is moderately dark.

In conclusion, attention is called to the fact that no experiments were made to determine the effects that the presence of rain and snow in the atmosphere have upon the point of initial corona formation. It appears from Mershon's Telluride results that there will be little effect from this cause.

With regard to the effect of the presence of smoke it should be said that there is evidence that a very slight loss is produced at all voltages, which is greater at the higher values due to this cause. During the spring of 1903, on days when the atmosphere was very smoky on account of neighboring forest fires, Dr. Blaker observed in the Physical Laboratory at Cornell that the conductive discharge through the atmosphere was appreciable when a continuous voltage of 15 000 was applied between wires of such size and separation that no detectable conduction occurred when the atmosphere cleared.

Those who have made line observations and who may use them to check the results given in this paper, must not fail to eliminate, first, the effects due to the presence of the supporting insulators.

It is altogether unlikely that changes in frequency, even over wide ranges, will affect appreciably the voltage at which atmospheric conduction is started when all other conditions remain the same.

Discussion of Paper by Harris J. Ryan.

C. F. Scott:—The paper we have just heard read is a remarkable one, and will probably be considered unique among the papers presented to our Institute. Our papers usually deal with results that have been accomplished, or with various methods of accomplishing ordinary engineering objects. This paper is of another order—it reaches into the future, and explores the unknown field of high-pressure work.

We can properly consider the work that has been done in high-pressure transmission in the light of an advance into an unknown and undeveloped country; some progress is made each year; within the last dozen years, pressures have risen by thousands and tens of thousands of volts; with each increase of pressure, new difficulties have arisen—new phenomena have appeared, new problems have come to the designer, to the operator, and to the experimenter. The paper is of particular interest, as it deals with things outside the present range of commercial practice, but toward which engineering work is now fast approaching. If this paper had been presented 15 or 20 years ago, it would probably have been regarded by the practical engineering world as visionary—something in the nature of static electricity, and something that active, practical people have little to do with; but to-day, engineering work is very near to those limits at which this paper indicates certain physical barriers to the further advance in power transmission.

The mention of the speaker's name in the paper, suggests some reminiscences of early work on this subject. It was about ten years ago that the need of experimental investigation of very high pressure became evident; little or nothing was known regarding insulators for high-pressure work, and it was a question whether there might not be some new kind of phenomenon involved which was not then understood. At that time, the maximum pressure of transmission apparatus was about 10 000 volts; the experimental work involved the manufacture of a high-pressure transformer, the making of tests on insulators and lines, and the exploring, in a general way, of the phenomena of high pressures. A transformer of 40 kw.—then quite large—was built, for a pressure of 40 000 volts at one step, and was used in the various tests. Discharges from the surface of insulators were noted; some of the lines that were run in the laboratory were 25 to 30 feet long, composed of small wires strung four or five inches apart, alternate wires being connected to the opposite terminals, making a network of high-pressure wires. As the pressure was raised, there was at first a slight hum, then a louder hum, and a glow, developing into a loud noise, accompanied by the smell of ozone; the appearance of light, sound, and ozone, appealing to the three different senses, meant the expenditure of energy in their production, and indicated a loss. Measurements of these losses were attempted, but the instruments at hand were not satisfactory, and the results not good.

Some time after that, as mentioned in Professor Ryan's paper, Mr. Mershon took up the work at Telluride, and succeeded, after overcoming great difficulties, in obtaining the results with which his name is connected, and which reflect such great credit upon his persistence and ability. Professor Ryan took up the problem where Mr. Mershon left it. Mr. Mershon had measured the losses, which were of considerable magnitude, and increased very rapidly above a certain critical voltage. Professor Ryan has put these results to the test of a rigorous experimental investigation, to determine the formula to express the beginning of this discharge, and has, moreover, investigated the exact nature of the discharge itself.

In the discussion of Professor Ryan's paper at Niagara Falls last Summer, the speaker took occasion to remark that his cathode ray indicator was valuable not only as a result of his research, and as a beautiful thing in itself, but also as a means—an instrument, by which results of a valuable character could be obtained. Now Professor Ryan has the honor to present to us a paper in which that instrument has been put to most excellent use.

SAMUEL SHELDON:—There are four distinctly different types of conduction through the atmosphere at ordinary pressures and temperatures; namely, the glow discharge, the brush discharge, the spark, and the arc.

The glow is blue-violet in color, is silent, forms in some cases a velvety covering over the electrode terminal, is a continuous discharge to the same extent as is the current from a primary or secondary cell, and exhibits a polar preference starting, with dissimilarly shaped electrodes, at a lower difference of electrode potential in one direction than in the other. It may be made up of an innumerable number of little convexions of electricity, as is a current which comes from any electrochemical source. The dielectric field strength at which this discharge is started has a minimum value. The discharge is maintained after this value is reached up to a certain limit, when the character of the discharge changes.

The brush is red-violet in color, gives a hissing sound, is probably intermittent in character, follows many unbranched paths which exhibit a tendency to separate from each other, and shows a polar preference similar to that shown by the glow discharge.

The spark is noisy, often follows forked or branched paths, and is often oscillatory in character. It is white in color but participates in the color of the incandescent vapors of the electrode materials. This coloring is prominent with iron electrodes and the characteristic ultra-violet radiations are very strong.

The arc discharge is familiar to all, has the color of the incandescent vapors of the electrode material, owes its conductivity largely to the presence of these vapors, and is quiet or makes characteristic noises.

The glow and the brush discharges are probably due to gaseous

ionization, and this corona discharge is probably a combination of both of these discharges. As the pressure rises, first comes the glow, and then comes the brush; and as it falls, the brush drops off and then the glow. There is a preference of polarity as shown in Fig. 4′ of the paper, where the little hump on the curve starts at a pressure of about 18 000 when the current is in one direction, and at about 21 000 when the current is in the opposite direction. This does not appear in Fig. 5′; but in Fig. 6, the pressure at the start of the prominent hump is something like 17 000, whereas the second hump starts at a little less than 20 000 volts.

The dielectric field intensity which is necessary to start a glow or a brush discharge in the atmosphere at normal conditions of pressure and temperature is smaller than that necessary to produce a spark. Therefore if the method of measuring high pressures which is suggested in the paper, be adopted, the breakdown value of 10 000 volts per inch in free air, which is the constant used in this paper and which is the value adopted by the INSTITUTE as a result of Steinmetz's experiments, should be abandoned and a new constant should be determined.

HAROLD B. SMITH:—As a discussion of this paper was not contemplated for this evening there is but one point which, possibly, may be added to an expression of most thorough appreciation which is felt for the work that has been done by Professor Ryan and of all that it signifies for the development of high-pressure work. He makes a reference in his paper to the form of electrometer which we have used successfully at Worcester for two or three years, for high-potential measurements. Some details of the way in which this electrometer was developed may be of interest. In 1901, four graduate students in electrical engineering at the INSTITUTE undertook the design and construction of a 500 000-volt transformer. In carrying out this work, we desired, after building the transformer and after getting discharges over spark gaps ranging up to four feet (1.22 metre), to measure the voltage; so it was proposed to use an electrostatic instrument measuring the voltages about the several coils of the secondary and adding them as a preliminary step. One or two of the men who were at work on this problem are in the audience and I presume they will remember the following circumstance. The electrostatic instrument registered as expected for the first few measurements, but the middle of the secondary of the transformer being earthed, as we proceeded away from the earth the readings became less and less, although it was known that the number of convolutions in the several secondary coils had been carefully counted and did not vary. A point was soon reached at which a zero reading upon the instrument was given and then reversed deflections of the electrostatic voltmeter were secured.

Proceeding from this point, the line of reasoning developed the conclusion that the absolute potential impressed upon the instrument was, in its effect, in excess of the effect due to the difference

of potential and so there resulted a repulsion of the parts of the electrostatic instrument in place of attraction as would ordinarily occur in the measurement of differences of potential. This at once led to the conception of the use of a *repulsion voltmeter* in which the fixed and movable parts were connected together and attached to a single wire leading to the instrument so as to depend wholly upon the repulsion due to the absolute potential of the system. This proved a peculiarly adaptable instrument for this work, where it was necessary to deal with potentials which would jump three or four feet, as it was necessary to lead but one wire to the instrument. Although the instrument was developed in this way, now that we have it in use it proves to be nothing more than an old-fashioned electroscope modified to meet successfully the conditions imposed by high pressures.

P. H. THOMAS:—In speaking of the apparent enlarging of the diameter of the wire to a certain pressure, does Professor Ryan wish us to think of the phenomenon as though we actually had a larger metal conductor, and that the electricity passes into the air and stays there within a definite volume? Or is it more probable that when it has once left, the wire will remain mobile, and the distance the charge passes over the surface of the wire will depend upon the time of duration of the excessive strain. If the latter is the case, we should find a difference, with different rates of alternations, unless the greater duration of time required for one alternation exactly balances the effect of the variations in a number of alternations; but the writer understands that no such difference has been found. Is this correct?

HARRIS J. RYAN:—The question cannot be answered very directly. This much, however, is certain: that one can pass very small currents through the atmosphere over large distances, with low frequencies, or with direct currents, provided that the wire is so small that the atmosphere breaks around its surface; ionization occurs, or electrons are set free, and they go from one wire to the other; but there seems to be no conduction of that character of sufficient magnitude to give rise to quantities that must be reckoned with in engineering.

P. H. THOMAS:—The speaker cannot conceive, at the present time, of a limiting surface to the air to which the electricity would go and there stop, without some further condition entering to determine physically the demarcation of the conducting space. Can Professor Ryan suggest any such idea? The air being a perfect gas, has, within itself, no force that can resist permanently at a definite point the tendency of the electricity to proceed further.

HARRIS J. RYAN:—In the experiment just cited, if the diameter of the wire is considerable at ordinary pressures, then there will be no discharge from one wire to the other. If the diameter of the wires is so small that at the pressure you apply between the wires, the atmosphere is broken around these wires, then there will be a discharge from wire to wire. In using high-pressure

continuous-current dynamos connected up in series for checking these experiments, one gets the conduction effect a little before the arc forms between wire and wire. However, with a Holtz machine you can produce a continuous pressure very much higher, and in the laboratory one can thus carry a small continuous current between small wires; for example, those having a diameter of three mils, from side to side through the atmosphere of a room. Such conduction will occur, however, only when the diameters of the wire are so small in relation to the pressure generated by the Holtz machine that structural rupture of the atmosphere occurs near the surface of the fine wires,—electrons are thereby set free, causing conduction. At certain larger conduction radii, dependent upon the pressure employed, appreciable atmospheric conduction will occur.

P. H. THOMAS:—In passing electricity through a vacuum, which is almost perfect, we have three electromotive force resistances to consider; one is the force preventing the electricity from leaving one of the electrodes, another preventing it from entering the other electrode, and the third, the resistance to passing through the vacuum space. The resistance to passing through the vacuum, with high exhaustion, is not very considerable, but is measurable. But with atmospheric pressures it must be tremendous. Have we not these elements in this case, or at least two, to consider; the force necessary to pass the current through the air and that of leaving or entering the wire? The resistance from the electrode is different from that into the electrode. If that is true, as Dr. Sheldon suggested, we should then find a difference between the positive and negative limits of the alternating current due to the electrode effect, though not the portion of the total resistance which is due to the resistance of the air. Possibly that may explain the slight difference between positive and negative which he notes. Have you found any difference between the positive and the negative?

HARRIS J. RYAN:—This matter has not been investigated and therefore the speaker has no knowledge of it. With alternating currents, of course, one conductor is first positive and then it is negative. The electrons are fired forth at one impulse and upon the following impulse they return again. With alternating current these phenomena are very hard to study. When we have very high continuous current dynamo pressures for laboratory work, those capacity phenomena that are ever present in our experiments with high alternating-current pressures will be eliminated, and with high continuous-current pressures this phenomenon can be studied with success.

P. H. THOMAS:—Different materials require radically different electromotive forces to pass electricity to the electrode. It would be interesting to study those materials which have shown the greatest differences in this connection. Aluminum and copper would be two which would have a different effect, probably. Have you not tried these metals, to see what difference there is?

H. J. RYAN:—Probably you are right, that the constants will be somewhat different for these different metals. Iron and brass and copper were used rather indiscriminately in determining the flux densities at which coronas are established in relation to changes in the curvature of conductors, and no noticeable difference due to these different metals was found, but the subject being new, the measurements are not refined enough to study these matters to best advantage. They are important, and some one should take them up and study particularly the manner in which flux densities are different for the aluminum with respect to copper.

P. H. THOMAS:—The speaker made direct measurements with a quadrant electrometer, used as a wattmeter, of the loss into air in a 50 000 volt circuit, nearly 100 miles long, the same instrument as described by Mr. Miles Walker before the INSTITUTE at the Great Barrington meeting. The losses began to be measurable at about the same pressures found by Professor Ryan,—that is, at from 20 000 to 25 000 volts, to ground; the loss increased very rapidly.

In the measurements made, the loss at 60 000 volts between the wires was approximately 10 kw.,—an insignificant loss as far as power transmission is concerned, but, nevertheless, very appreciable.

P. M. LINCOLN:—In reading over abstract of Professor Ryan's paper on "The Conductivity of the Atmosphere at High Voltages," the questions which are apt to occur to the practical high-pressure engineer who has a line to operate are:

1—Is there any loss in my line due to the effect which Professor Ryan calls the "corona" effect. If so, how much?

2—If these losses are not taking place at present pressure, to what extent will they enter if pressure be raised?

3—If these losses are taking place, what remedies can be applied to prevent?

How far are these questions answered by the paper which Professor Ryan has presented? To the first question the answer seems to be definite and complete. We may readily determine from the formula that for the worst conditions which would occur in actual practice; viz: a No. 6 wire with a spacing of say forty-eight inches, this corona loss at sea level does not begin until the voltage has reached the neighborhood of 100 000 effective. For the maximum altitude at which transmission is apt to be carried on, say 10 000 feet above the sea level, the pressure at which the loss begins may be as low as 65 000 for the worst cases, but even then the pressure at which the corona loss begins is still considerably beyond the limits of the actual practice of to-day. The question of corona loss, therefore, is evidently one for the future to decide and not one which should disturb high-pressure engineers of to-day.

The formula which Professor Ryan gives at once tells us the pressure at which this corona loss begins to appear, and the other data cited apparently checks this formula closely. The

voltage at which this loss begins depends upon borometric pressure, temperature, radius and spacing of the wires, and upon two additional quantities designated "d" and "D'." These two last mentioned quantities are, so far as can be judged, from the abstract at hand, empirical in their nature. The pressure at which the loss begins is apparently entirely independent of frequency.

When we come to the second question, the answer is not so complete. To know the pressure at which this form of loss begins is of course important but it is even more important to know how much it amounts to for any given voltage excess above the point of beginning. For one particular case, which by the way is entirely outside the realm of practice, Fig. 7 gives the answer. What the relative losses are, however, for conditions which would occur in practice the paper leaves undetermined.

Normal progress is bound to carry transmission pressures beyond those that exist to-day, therefore the third question as to remedies to apply has a decided bearing. It is well known that a good rubber insulation on the wire will almost entirely prevent this corona loss, at least within the lower limits of pressure at which the effect occurs.

It would be interesting to determine the effect of various kinds of insulation on the wire, in so far as their influence in preventing this loss is concerned.

The method applied by Professor Ryan is most ingenious and we hope that the record of the work done by him which is given in this paper is not the last which will be done along similar lines.

[COMMUNICATED AFTER ADJOURNMENT BY G. T. HANCHETT.]

In 1895 the writer investigated the visible phenomena surrounding the electric discharge, and having no large sources of potential at hand, used an ordinary 1-inch induction coil, and viewed the discharges under the microscope. Two terminals of thin metal foil were gummed to the slide of the instrument, and arranged so that they would appear in the field of a 0.25 inch objective, and passed discharges between them of varying strength. One of the most interesting points developed was that the negative terminal was distinctly hotter than the positive terminal, and when the discharge had reached the sparking point, the negative terminal melted very rapidly, while the positive remained practically intact.

Professor Ryan's investigations of the effect of temperature on the dielectric strength of air, together with this phenomena, seem to explain Dr. Sheldon's remarks about the difference of potential required to strike between a knob and ball. When the point is the negative, the heat developed there is concentrated, the temperature is high, and the air breaks down easily at a low pressure. When the point is positive, the heat developed by the discharge, being large at the negative pole, is readily radiated by the large surface of the ball, the temperature is lower, and the discharge does not find as easy a path.

Concerning Mr. Scott's remarks about the ozone that is generated, it might be interesting to add that in case of direct currents it is easily shown that ozone is generated in larger quantities at the negative pole. The most convenient means of detecting this is a solution of starch and potassium iodide.

Not the least feature of interest in Professor Ryan's paper is his denial of the theory that a moist atmosphere necessarily involves great leakage. His experiments conclusively show that this is not the fact, and we may therefore attribute any additional leakage which our lines experience in moist weather entirely to the accumulation of moisture on the insulators, and not at all due to the increased tendency to brush discharge leakage through the atmosphere itself.

[COMMUNICATED AFTER ADJOURNMENT BY ELIHU THOMPSON.]

The paper of Professor Ryan brings out clearly the relation between the different factors which combine to influence the voltage at which atmospheric loss begins or becomes serious. He has been able to deduce a formula for calculating that voltage under varying conditions of atmospheric pressure, temperature, etc. The data obtained by Mr. Mershon and Professor Smith are shown to fit in with Professor Ryan's results. As he points out, the lower values of effective voltages obtained in the Smith observations are without doubt due to the distortion of the wave form into one more peaked. The true character of the atmospheric loss is pointed out by Professor Ryan in connection with his very interesting plottings in Figs. 3′, 4′, 5′, and 6′. The loss is due to an enlarged capacity-current working over the high resistance layer, which virtually adds to the diameter of the conductor. The addition of this broken-down air layer takes place at a critical voltage and its amount rapidly increases with any increase beyond the critical value. In Fig. 6′ the effect is that of a greatly enlarged capacity coming into existence at something under 20 kilovolts in Professor Ryan's experiment, if the writer correctly interprets the results. In Fig. 3′ the voltage wave attains a maximum of 22 kilovolts without showing the indications of atmospheric loss. Increasing the voltage as in Figs. 4′, 5′, and 6′, shows that the upward bend of the charging current curve begins at a value considerably below 20 kilovolts. This may be due to ionization or heating of the air layer by the prior waves. If this be true it should become more pronounced at higher frequencies. It might probably be a useful extension to study the effects when the conductor was kept hot and cold air circulated about it, and also the result when the conductor being maintained at a much lower temperature than the surrounding air. The highly interesting and practical results obtained by Professor Ryan serve as an illustration of the value of the inertialess cathode ray wave indicator in the development of which he has succeeded so admirably.

[COMMUNICATED AFTER ADJOURNMENT, DISCUSSING "THE CONDUCTIVITY OF THE ATMOSPHERE AT HIGH VOLTAGES." BY RALPH D. MERSHON.]

This paper takes up a number of points which the writer was desirous of attacking at Telluride, but which lack of facilities prevented.

The fact that the critical point in the loss curve; *i. e.*, the point at which the atmospheric loss suddenly begins, is marked by the beginning of luminosity was appreciated by the writer in the Telluride work, and made use of to a slight extent in studying the question as to the influence which the material and the condition of the surface of the conducting wires had on the critical point. It was found that the condition of the surface as to its roughness had a very decided bearing on the critical point, any roughness causing it to occur at a much lower voltage than with a smooth surface. There was apparently also some difference in this regard due to the material of the conductor.

Luminosity, however, is not the only evidence of the critical point. The rustling or crackling sound, very apparent in the case of an overhead line, is also coincident with it; also, curious as it may seem, the critical point is indicated very accurately by the twitching of the hair and moustache. This was first noticed in some readings on a wattmeter inserted directly in the high-voltage circuit and over which the observer had to lean, bringing his face and body within 18 to 24 inches of the instrument. The metallic case of the wattmeter was connected to one leg of the circuit in order to take advantage of the shielding action of the case against any electrostatic influence. A number of trials showed that the observer could, with fair accuracy, tell when the critical point had been reached.

As to the question of frequency, the Telluride measurements were conducted at a frequency of 60 cycles and also at 30 cycles, but no difference could be detected which could not be laid to errors in the instruments.

There are two points in which Professor Ryan's paper is in error. The work at Telluride was done in 1896–1897; the measurements were made at voltages as high as 72 000 volts and a voltage as high as 133 000 volts was impressed upon the line. No measurements were taken, though several photographs were secured at this latter voltage.

Referring to the possible contention, mentioned on page 302 of Professor Ryan's paper, that the line-loss curves of the writer's paper should be abrupt, there are some other points in support of Professor Ryan's view. One of these is that the line wires could not be absolutely the same through their length as to roughness and that at the rough portions the loss would first begin. This was very apparent when viewing the Telluride line at night. The line became luminous in spots, which at first seemed equally spaced but which closer examination showed to be unequally spaced. As the voltage was raised other luminous spots grad-

ually developed at points intermediate to the first ones, and this action continued until the whole line appeared more or less luminous but never uniformly so. The spots were never far apart, always at intervals small enough so that at a little distance the line suggested a string of luminous beads, and it shows as such in the photographs taken. Each one of these luminous beads had a bunch of fine purple streamers from it. Another reason in support of Professor Ryan's view is that an alternating e.m.f. is dealt with. At first just the top of the wave rises above the critical voltage and as the voltage is raised, more and more of the wave is effective above the critical value. This in itself tends towards a more or less gradual increase in the loss curve.

[COMMUNICATED AFTER ADJOURNMENT, DISCUSSING "THE CONDUCTIVITY OF THE ATMOSPHERE AT HIGH VOLTAGES." BY S. M. KINTNER.]

The writer's experience with the coronal formation on high-voltage lines leads him to believe that the surface condition of the wires is a factor that enters quite largely. This condition can hardly be incorporated in any formula expressing the relation among the various factors involved. An instance of this was quite forcibly brought to the writer's attention while working with an arrangement of horizontal wires as a Hertz oscillator. This oscillator had another circuit in proper relation to it to prolong the oscillations set up. The horizontal wires were bare copper, about No. 16 B. & S. gauge, carefully insulated from and parallel to the earth, at a height of about six feet, both ends of the wire oscillator being the same length. On carefully adjusting the oscillating period of the auxiliary circuit to that of the wires, as was told by two independent tests, and viewing the wires in the dark when the power was on, they were seen to glow very decidedly throughout about two-thirds of their length, the glow being strongest at the ends and tapering down to darkness towards the middle. One wire was noticeably brighter than the other. An examination of the wires showed that one was old and very much weathered—this one glowed the brightest—while the other was new and had been exposed to the weather for the first time. On the substitution of an old wire for the new, the glow was practically the same.

Another point, suggested by the reported experiences of the Marconi Wireless Telegraph Company, in which they found it much easier to send messages by night than day, is the question of the action of light, ultra violet, etc., upon the formation of the corona and line losses at high voltage. It seems most likely that there is some such action.

An examination of Professor Ryan's formula brings out the great sensibility of the coronal formation to temperature variation. A variation of 5° fahr. causing 1% variation in the voltage at which this phenomena takes place. Taking as extremes of temperature variation for cases that would likely occur on transmission lines—say – 25° fahr. to 125° fahr.—a range of 150°, which would mean a 30% variation in the critical voltage.

Discussion on "The Conductivity of the Atmosphere at High Voltages," at Pittsburg, March 10, 1904. By H. W. Fisher.

The speaker has never made experiments to determine line losses due to very high pressures. He knows, however, that unless the cable is well made, said losses can be considerable and the cables become very warm in consequence. When cables are being tested to from 30 000 to 60 000 volts, the ends have to be very thoroughly protected or else there will be long discharges over the insulation near the ends. A short time ago the speaker made a test of 55 000 volts between conductors of a non-leaded cable on a wooden reel. The particular cable in question had three conductors and a test was made between one and the other two. All the spaces between the convolutions of cables were beautifully illuminated, and the noise of the discharges was loud and almost enough to make one feel nervous. The energy loss here must have been considerable because the cables became very warm.

The speaker has obtained some beautiful and extremely interesting corona effects when making measurements of the spark distances corresponding to different voltages and different kinds of points. The tendency to brush discharges is apt to cause an actual spark to take place at distances which are not always normal. To obviate this, he has used concave discs whose edges are slightly back of the needle points, and by doing this he has obtained much more uniform results.

A paper presented at the 184th Meeting of the American Institute of Electrical Engineers, New York, February 26, 1904.
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EUROPEAN PRACTICE IN THE CONSTRUCTION AND OPERATION OF HIGH-PRESSURE TRANSMISSION LINES AND INSULATORS.

BY GUIDO SEMENZA.

In Europe, as in America, the old practice in overhead line construction has always been to consider the construction of an electric transmission line work that any man could do. It was sufficient to erect a number of wooden poles, fix on them some insulators and stretch some wires, and everything was expected to work well. The line was considered the simplest and the easiest part of the plant. It is true, on the contrary, that the line was the part which gave the greatest trouble; but the line constructors placed the blame upon atmospheric disturbances. It was only at the time of the Paderno (Italy) installation in 1895, I believe, that new views were entertained on this problem.

The new way of considering the matter, originally due to Mr. Roethlisberger, an engineer of great skill in metal frame constructions, was the following: an electric transmission line, being a structure every part of which has to bear certain strains, must come under the general head of engineering work, as would any similar structure. You carefully calculate a bridge; why should you not avail yourself of the benefit of statics and dynamics to make your line the strongest and the cheapest? No objection could be made to this simple reasoning and the Paderno line was constructed in accordance with these considerations.

Following this principle, new solutions and views were gradually entertained, and the different matters treated of in this paper are to be considered the result of a study of the subject by many engineers.

The first question which requires consideration when a line is to be built and the pressure of the current has been fixed, is; which is the most advantageous wire-section to be adopted? In a line you may allow any loss of energy, say between 2 and 20 per cent, but what will be the most advantageous value, considering both the cost of construction and economy of operation? In some instances the line-loss is limited by the regulation required

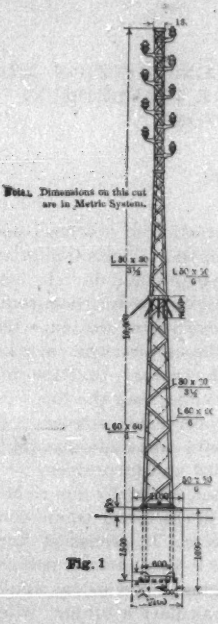

Fig. 1

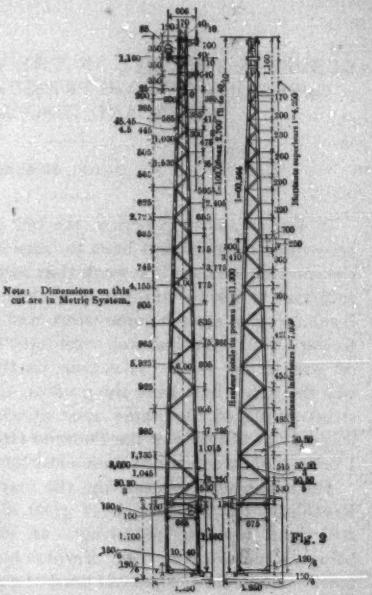

Fig. 2

at the end of the line; or in cases of small powers and high pressure, by the minimum section of the wire required to give the necessary mechanical strength; in other cases, the problem is generally purely one of economy. In the old practice, the most economical wire cross-section was determined without the aid of any calculation, in quite an empirical way based on the consideration of gross expenses, weight of wire, etc. However, a close examination of the subject shows this to be an important factor of economy.

I beg to refer you to a paper on this subject I presented to the Italian Association of Electrical Engineers, in which the problem is exhaustively treated, so I shall refer here only to the principal points. The greater the weight of copper, the less the loss; so that by increasing the wire section we incur a larger outlay of capital and annual fixed charge in order to increase the possible income. But, while the income as a function of the copper-loss follows a linear law of variation, the outlay of capital follows a hyperbolic law. Consequently, at one of the limits we arrive at zero income for a definite expense, and at the other limit a definite income for an expenditure infinitely large. Between these two limits there must be, in each particular case, a value of copper-loss for which the profit from the undertaking is a maximum or any other economical condition is fulfilled. The condition to be arrived at or to be fulfilled must be determined from the data of the problem. Supposing, then, that the following values are known, namely: power produced; cost of installation; selling price; operating expenses; the value of the copper-loss which will bring a maximum profit can be found. On the contrary, when the selling price is not fixed, the value of the copper-loss which reduces to a minimum the anunal cost per kilowatt utilized may be the quantity to be determined.

These problems may be worked out in an analytical way by writing down the equations and solving them by the differential calculus. But it is much better to draw the curves of the different elements and compose them. The graphical method permits one to take into account, in their true significance, some elements which vary according to laws we are not able to express by analytical functions: for instance, the value of poles and insulators, which is not a constant, but varies with the number and section of wires, and especially all the quantities which enter into the problem when an auxiliary steam station has to be resorted to, as, for instance, the consumption of coal, the hours of utilization, etc. Moreover, the results which we obtain by the graphical method show quite clearly the behavior of the resultant value towards the maximum or minimum found, allowing a certain latitude in their adoption. An analytical expression gives an isolated figure without showing very much of the curve to which it belongs. This method is an amplification of the well-known Kelvin law and permits one to apply the principle of this law to any case, however complex it may be. When the pressure and the cross-section of

wire have been fixed, the question of the route of the line arises. In Europe, generally speaking, important lines are carried across the country and not alongside roads; this is done for obvious reasons. The cross-country method allows the building of a straight line, thus avoiding angles to a considerable extent; then, again, the line is shorter. Of course, crossing cultivated land, as is generally the case in

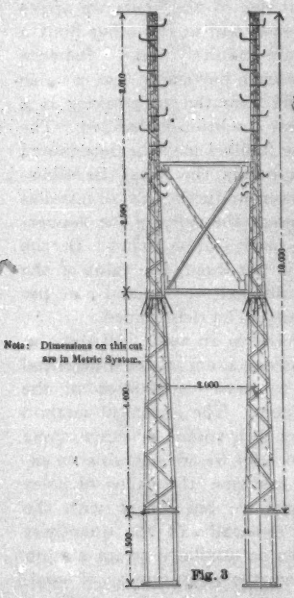

Fig. 3

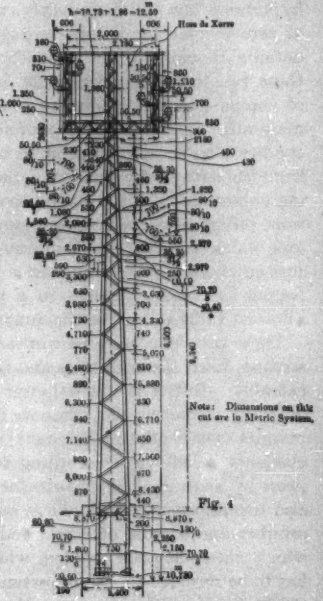

Fig. 4

Europe, the cost of building the line is increased on account of the expropriations; but in the greatest number of cases, the extra cost of purchase of land or of right of way, is more than compensated by the shorter line. It must not be forgotten that the weight of copper increases in the ratio of the square of the length of the line, the loss remaining the same. It is often argued that following the high roads, the patroling of the line is much easier, but in many cases the right of way along

the line across the fields is included in the purchase and the system proves very efficient. At all events, well-constructed and straight lines far from the roads do not show the necessity of very close patrolling, although it is prudent to exercise it.

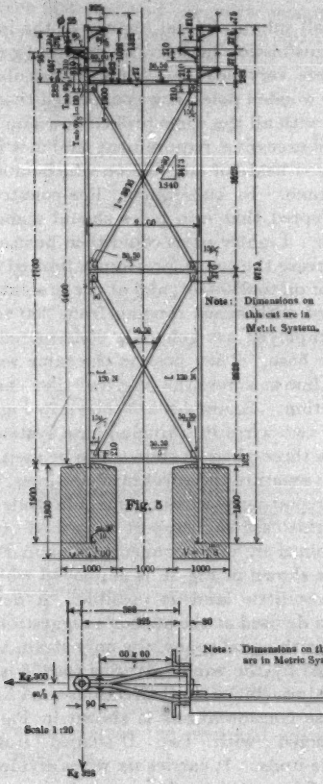

Fig. 5.

Fig. 6.

A most important question now arises: whether metal poles are better than wooden poles? The principal reason for the adoption of wooden poles is the small cost of installation. For small lines

this may be true. Another reason is the assumption that wooden poles increase the insulation of the line; and this also is true, but only when the insulators are very bad. A close investigation, however, will lessen the advantages claimed for wooden poles.

First of all, I shall submit a brief history of the introduction of iron poles for transmission lines. The first iron poles erected for this purpose were very heavy. While no calculations were made for lines with wooden poles, it was expected that iron poles should stand, even with all the wires broken down on one side of them. This was an excessive requirement and not in the least justified; I have never heard of any line on which more than one wire broke at a time. In subsequent line-construction the hypothesis was accepted that iron poles should stand with one or two wires broken. Lighter poles could then be used. It was then possible to increase the spans, previously limited to 100 feet, to 200 feet, and later on to 250 feet; and at the present time some lines are constructed with spans ranging from 300 to 400 feet.

The iron poles employed are generally constructed of lattice-work with a square base. They possess the same resistance in the direction of the line as across the line, and they can resist the strains in any direction. Examples are shown in Figs. 1 and 2.

When more than two wires in a single-phase system, or more than three wires in a three-phase system are to be used, it may be found convenient to separate the wires into two lines, in order to render possible the repairing of wires on one side while the others are in circuit. In this case the support is formed of two poles placed apart and joined by cross-connections as in Fig. 3, or a support like the one shown in Fig. 4, is employed when it is important to occupy as little land as possible. A new form of double pole has been devised at the author's suggestion.

On straight lines with equal spans, the only strain to be borne by the line is exerted by the wind. In this case it is useless to employ poles of equal resistance in all directions. A line support constructed on these considerations is shown in Fig. 5. This support is constructed with two U-shaped irons, cross-connected with angle-irons. It carries six wires divided into two sets, two metres, 6.5 feet, apart. Having a very wide base, it presents a great resistance in the direction of the wind and a low resistance in the direction of the line, in which direction it is elastic and can deflect over 16 inches without exceeding the limit of elasticity, and is called the "elastic support."

In the event of one or two wires breaking, the two nearest poles will bend, which will discharge the following spans; and calculations show that the entire line will stand and no injury will be done to the supports. These poles are employed for spans of over 300 feet and are very economical. In fact, an elastic support for six wires and for a span of 300 feet weighs about 1000 lb.

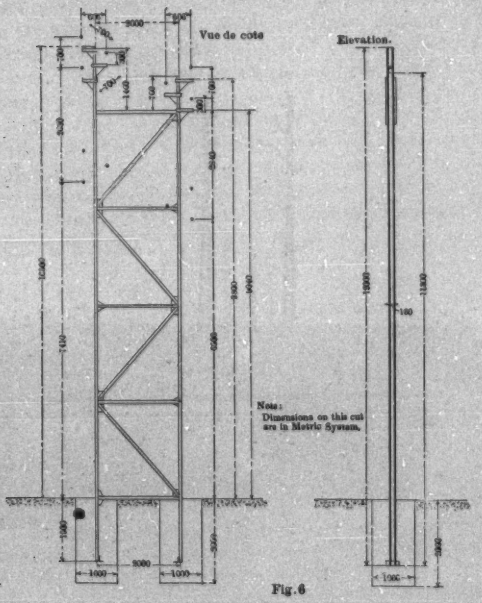

Fig. 6

I shall now enumerate the principal advantages and disadvantages of iron poles.

ADVANTAGES.

Duration—Wooden poles will last from two to ten years, according to the nature of the ground. The durability of iron poles cannot be definitely stated as yet, but they will surely last 40 years, reducing the depreciation to a small amount.

Large Spans—Spans with iron poles may reach from 300 to 400 feet and in exceptional cases to 600 feet and more. This compensates for the higher cost of single supports, as in lieu of three or four wooden poles one iron pole can be adopted, reducing the number of insulators and consequently of weak points, and thus

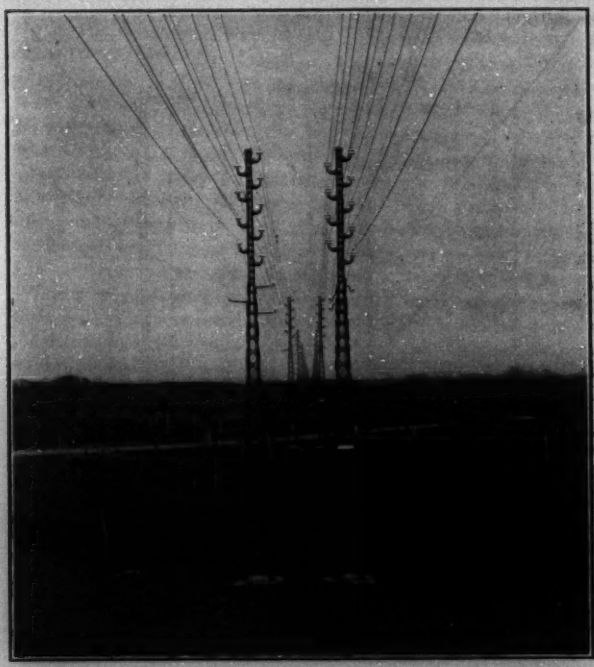

FIG. 7.

rendering possible the crossing of difficult passages, as shown in the examples which follow.

Lower Cost of Maintenance—The experience with existing lines constructed with iron poles, shows that the expense of keeping the line in proper repair and good working condition is very much reduced. With wooden poles the strain exerted

by the wires will slightly displace the poles or rotate the cross-arms. Dry or wet weather will lessen the connections between cross-arms and poles and between pins and poles. In some cases wooden poles will twist in time.

All the above facts affect the insulators, pins, and bindings, so that a certain amount of work is constantly required to keep them in good order.

In line-construction with iron poles, all these causes of deterioration are avoided and lines which have been in use from five to six years are in as perfect condition as they were when first constructed. The poles require repainting only every four or five years.

DISADVANTAGES.

A Somewhat Greater Capital Investment—To illustrate this point, I submit the following figures, showing the difference between a line constructed with wooden poles and a line constructed with iron poles, based upon European prices and for a three-wire line for high-tension transmission.

Wooden Poles.		Iron Poles.	
53 Poles at $6.00	$318	16 poles at $24.00	$384
3 x 53 = 159 Insulators with brackets, at $1.00	159	Concrete Foundation at $9.00	144
For right of land occupation, $2 per pole	106	3 x 16 = 48 Insulators with brackets, at $1.00	48
		For right of land occupation, at $2.00 per pole	32
	$583		$608

Better Insulators Required—As a matter of fact, the breaking of an insulator means a complete grounding; but as we shall see, the insulators which can now be obtained reduce the frequency of this disturbance very much. On the other hand, it is not always true that wooden poles act as insulators as, for instance, in wet weather one cannot depend upon the surface-insulation of wood. Concluding, from an economical point of view, iron poles require a larger capital investment; but the maintenance and depreciation are reduced to a minimum. These considerations tend to make the adoption of iron poles for important transmission lines more and more general.

We shall now proceed with the consideration of the best method to be pursued in the construction of a line, more espe-

cially with reference to important lines. When the land across which the line is to be constructed has been decided upon, a careful survey is made and a map drawn, on which the location of each pole is marked, the angles and eventually the prescribed height of the lowest wire from the ground. The single supports are then studied and calculated. These are divided into two classes; namely, normal and special. The normal supports are intended for small angles, equal spans, and normal height. The special supports are those which have to meet special conditions.

Iron poles are calculated by the ordinary rules of mechanics. The forces acting on the poles are: the weight of the pole itself; the wind (both on poles and wires), and the strains transmitted by the wires. With equal spans on each side of the pole and no

FIG. 8.

angles, the only forces acting on it are: the weight of the wires and the wind. When spans are not equal, there is a longitudinal strain which varies with the temperature. If an angle occurs, there is a component of the strain exerted by the wires which acts in a transverse direction. In the case of a vertical angle there will be a vertical component.

We must then begin with the calculation of the strains exerted by the wires. In doing so the effect of wind and snow must be taken into account, allowing a tension which does not exceed the limit of strain admitted for copper in coldest weather and with an overload of snow and ice. The maximum sag is also calculated in order to determine the height of the pole, as the wire

must never come too near the ground. Taking into consideration all the above facts and effects, the poles are calculated in the same way as any iron structure.

We must also calculate the weight of the necessary foundation, which must be sufficient to resist the overturning moment. In this calculation the resistance of the earth surrounding the concrete foundation block is also taken into account. This having been done, the profile or ground cross-section is completed, by marking on it all the aforesaid data, including height of poles,

FIG. 9.

sag, strains, etc. The strains exerted by the wires being transmitted to the poles through the insulators and the pins, these must be considered from a mechanical point of view, and calculated in accordance therewith.

Wooden cross-arms are sometimes employed with iron poles, in which case any system of pins may be used; but in general, supports constructed entirely of iron are preferable. In this case either iron or steel pins are used on brackets composed of angle iron, as in Figs. 2 and 5, or even entirely of cast-steel, as can be seen in Figs. 1 and 4.

A special cement is employed to fasten the insulators to these brackets, or, in the case of small lines, tarred rope is employed. This differs entirely with American practice, and no attempt is ever made here to use threaded insulators, as it is difficult to obtain good insulators with thread of the exact gauge. The best cement that can be employed for this purpose is composed of ten parts of litharge and one of glycerine, well mixed.

The brackets and insulators cemented together with such a mixture form an indivisible unit, which must be replaced when-

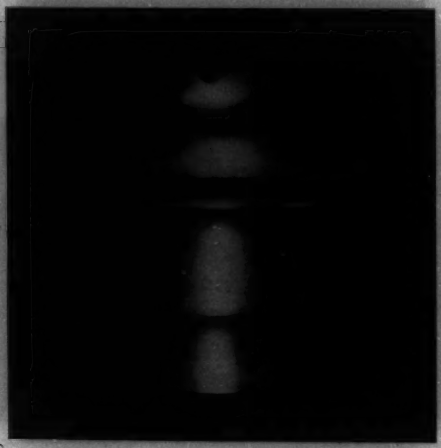

FIG. 10.

ever the necessity arises to change one or more insulators; but on the other hand, the mechanical resistance is undoubtedly much higher. In fact, in a cemented insulator the pressure between pin and porcelain is equally distributed over a large surface; while with the threaded-pin system, a slight bending causes the insulator to break, as it will in this case press against one point of the pin. The author has often tested insulators cemented on 1.5-inch rods, and always succeeded in bending the rods without breaking the porcelain.

When the span exceeds a certain length, care must be taken that the wires do not come in contact through their oscillation due to the wind. It is obvious that in order to avoid such a contingency, it is necessary that two or more wires should never be placed on the same level, and the adoption of cross-arms as practised in America is not to be followed. In any case, it is easy to calculate the deflection of the wires from their vertical position, due to the force of the strongest wind prevailing in the country and midway of the span, thus finding the distance between the insulators to prevent the wires coming in contact.

In the cases represented by Figs. 4 and 6 another solution is adopted: a line of six wires is divided into two sets of three wires each, one set on each side of the support and placed at a different height. Calculation shows that, if the two sets were placed at the same height, the wires would come in contact.

Fig. 7 shows a view of a line constructed following the aforesaid principles.

One may ask if it is worth while to make such a careful calculation. That is easy to answer: in order to reach a high economy in the use of iron poles, it is necessary to put in them only the quantity of iron that is absolutely necessary; and this cannot be done without a close calculation of every element of the line. The author had the opportunity of calculating the poles of a line built without much precaution, and found that each pole weighed about 200 pounds more than was necessary. As the number of poles was 600, the extra weight represented a total of about 60 tons of metal in excess of what was actually necessary.

The problem of high-pressure insulation is very carefully studied by European electricians. It is well known that glass insulators are not used in Europe and the reason for this, I believe, is that good porcelain can readily be obtained here. Glass is considered to have a better dielectric strength, but not as good surface insulation; moreover, glass is weaker against meteorological agencies, the superiority of porcelain being due to the materials composing the glazing. It must be said at once that European engineers do not consider American porcelain as good as European porcelain. It is possible that they may be mistaken, but a few tests made by the author on American insulators showed a higher dielectric resistance for the European porcelain which in appearance, finish and homogeneity of material is much better. Perhaps the difference in these particulars may have had much to do with forming his opinion.

In this connection I might mention that it is the general practice to examine all insulators on their arrival from the factory and put aside such as present a bad appearance; viz., such as are not glazed all over the surface, or that have cracks, spots, etc. This examination is performed by an ordinary workman specially trained and the pieces set aside are subjected to particularly severe tests. A few hundred insulators of American manufacture came over to be tested, and they were put through the usual examination. When the inspector came around, he found that all his American insulators were put to one side for surface faults. It must be said, however, that these insulators stood all the tests quite well.

The fact is that in Europe insulators may be obtained quite perfectly finished. It is considered necessary that the head and all external parts should be thoroughly glazed; to insure this they are supported from the bottom in the baking process. Another advantage in favor of European insulators is that the factories are willing to make any shape desired, which facilitates the introduction of new types.

In designing an insulator the following points are to be considered: dielectric resistance; resistance against surface-arcing; mechanical strength; facility of cleaning; ease of construction.

The first two points have reference to electric qualities and an ideal insulator ought to be so proportioned that, under a certain voltage, it should break in both ways, by puncture and by surface-arcing. It is well known how the resistance against puncture can be increased, by making the insulators of several pieces, introduced one piece inside the other. In general, the different pieces are cemented together with a kind of glazing in the process of manufacture and put on the market as single pieces.

The author does not follow this practice but prefers having them furnished by the factory in separate pieces, for the following reason: when the thickness of the porcelain reaches a certain limit, the ordinary testing will not puncture a sound insulator. In testing an insulator made up of two or more pieces, one layer of porcelain may be cracked but is protected by the other layers. When the tests are performed on the single composing parts, this cannot happen, and one is sure to have the insulators made up of sound parts. Moreover, each composing part can be better inspected and the character of glazing observed. Following this suggestion many factories produce insulators in two parts, which after test are put together with glycerine and litharge cement.

Experience has demonstrated that it is useless to increase the number of component parts; up to 40 000 volts two parts are quite sufficient and above that voltage not more than three are necessary.

The ability of an insulator to resist surface-arcing is due to its dimensions and shape, the latter to be considered under a double aspect: 1. The protective action against moisture and rain; 2 The property of giving origin to electrostatic phenomena. An insulator with a very large petticoat on the top and only a second petticoat round the pin will not afford a

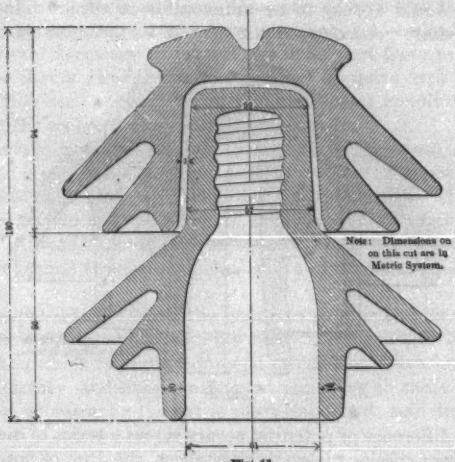

Fig. 11

very good protection against rain and moisture, as during a storm the inner petticoat will get quite wet. It is therefore good practice to have one or two intermediate petticoats, which will also ensure the dryness of some part of the surface in all kinds of weather. Care must however be taken not to put on too many of them, as their edges would come too near, thus forming a good path for the arc, besides increasing the difficulty of cleaning the insulator.

With reference to the influence of electrostatic phenomena on surface-arcing it is only possible to venture some assumptions, although it appears that they have a certain basis of fact. It is well known to those who have studied tests on insulators, that the surface-arcing does not always occur at once, but seems to be preceded by a number of static discharges between the petticoats. These discharges, of a bluish color, are very marked with insulators having petticoats close together, in which arcing seems also to occur with larger air spaces. It is not improbable that these blue discharges may produce an ionization of the air and moisture, which facilitates the striking of the arc.

This would appear to be unfavorable to the introduction of intermediate petticoats, and it may be further pointed out that

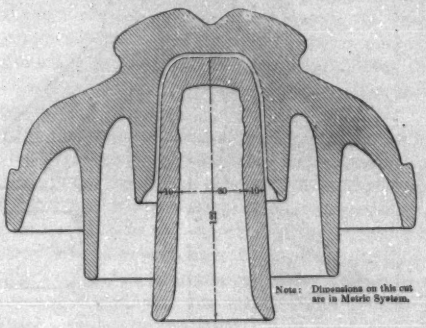

Fig. 12

when a difference of potential occurs across a series of dielectrics of different specific dielectric resistances, the drop of potential is distributed not uniformly, but in proportion to the dielectric resistances. Suppose then an air-gap so arranged that the drop of potential is 1000 volts per inch and that we introduce a porcelain diapraghm, the drop of potential per inch in the two resulting air-gaps may then be higher than 1000 volts per inch. Again, as it is desirable to have a low line-capacity, an insulator with a low capacity is to be preferred. Mr. F. Carcano has lately succeeded in comparing the capacity of different insulators by a very ingenious method.

He arranged a Wheatstone Bridge with two equal capacities, a and b, a variable capacity c, and the insulator to be measured,

of which we will call the capacity, x. In the place of the battery he connected a generator of electric oscillations, and in the place of the galvanometer a vacuum tube. When c is different from x the tube is bright, when by adjustment it is made equal to x, the tube is dark. By this method he was able to prove that the capacity of insulators of the various shapes used, vary from 1 to 1.9, a very large difference. The lowest capacity is shown by the insulators which have a few petticoats and one very open at the top, while the higher capacity is shown by those those which have two or more petticoats close together, and more so if the outer petticoat drops and surrounds the others.

From all these facts and considerations we arrive at the conclusion that the use of intermediate petticoats is to be limited to those strictly necessary to protect the inner part from rain and to ensure that a part of the surface shall be quite dry. Insulators which are supposed to meet the aforesaid conditions are shown in the annexed photo-prints and drawings.

The insulator shown in Figs. 8 and 11 is composed of two pieces and is used for voltages up to 30 000 volts. The petticoats are conical and have an inclination of about 45°. The two insulators shown in Figs. 9 and 10 are composed of three pieces and are intended for 40 000 volts. All these insulators have good mechanical strength, which is also an important consideration.

This paper which I have the honor to submit to you, shows one of the ways in which you may study a transmission line; it is a method which requires study and calculation, but the results are satisfactory, and lines constructed according to these principles are economical and, what is most important, safe in operation.

Discussion of Paper by Guido Semenza.

(J. W. Lieb, Jr., read the paper, and in conclusion, showed a number of lantern slides embodying details of construction of Italian pole lines for power transmission.)

W. N. Smith:—It is to be regreted that the author of the paper is not present to describe in detail the practical operation of the construction shown. The author concludes his paper by saying that "the results were satisfactory," and that the lines were "economical" and "safe in operation." The methods outlined are so different from those in this country that it would seem very desirable to get in closer touch with the European engineers, and compare their results from operation with ours. A thorough discussion of details would tend to show clearly whether their methods are really an advance upon ours. The paper is an unusually valuable contribution to the cause of power transmission.

B. J. Arnold:—There is a transmission line nearly completed in Mexico, very similar to the construction described in the paper; it is one hundred miles long, built with steel towers of the regular windmill type, using from seven to twelve poles to the mile. This is supposed to be the most modern transmission line in existence.

The New York Central Railroad Company has decided that it is safer and more reliable to have its transmission lines overhead on steel poles than to place the wires in conduits; this decision is substantiated by information secured from different transmission lines in operation in this country. Every competent engineer who was consulted, advised the company to put the wires overhead if possible, because it is easy then to locate trouble promptly and to make repairs, while if wires are underground in conduits, it is difficult to locate trouble and difficult to make repairs.

L. L. Perry:—The type of European construction illustrated in Fig. 3 would seem to have been developed largely on account of the narrow streets requiring wires to be placed one above the other. This form of construction is a poor one for making intersections; a line of twenty or so wires so set would require a pole 50 or 60 feet high.

W. S. Dix:—A disadvantage of long horizontal spans is the possibility of adjacent wires touching; the vertical arrangement of the wires would obviate this trouble. American manufacturers of insulators are now following out the lines suggested by the author, and are reducing the number of petticoats, increasing the surface, and increasing the distance between petticoats,—thus reducing the arcing across. The insulators used at Shawinigan Falls have three petticoats, widely separated, and with these there has been no trouble.

W. N. Smith:—It is not clear from the figures that the three wires of a circuit are arranged at the points of an equilateral triangle. Do European engineers ignore the supposed advantage

of putting three conductors at the points of an equilateral triangle?

J. W. LIEB, JR.:—Several of the lines show clearly that a perfect equilateral triangular arrangement is intended.

C. F. SCOTT:—There has been a great difference between engineering work done inside of the power station and that done outside of the station. The development of electric apparatus has, in general, been in the hands of a few manufacturing companies with a corps of expert engineers, who have developed the machinery to a very high degree of perfection. In general it is thought that any one can run a pole line, and the engineering of it is left to the wireman. The outside construction has been haphazard; it has been handled by many local companies with little or no consideration for engineering requirements; some of these companies have done their work well, but, in general, external construction lacks standardization, uniformity, and fails to receive the higher grade of consideration that has been given to other departments of the work.

Mr. Semenza showed the speaker through the installation in Milan, and over the Paderno pole line; this line has the appearance of solidity and of being expensive, although the figures of cost given in the paper indicate that it is not unusually high. The substantial construction of the line and the respect which is shown to railroad crossings is a thing which impresses an American. The set of downwardly-projecting fingers about halfway up the poles renders the construction fool-proof as well as mechanically substantial.

(A vote of thanks was given to Professor Ryan and Mr Semenza for their papers.)

Discussion on "European Practice in the Construction and Operation of High-Pressure Transmission Lines and Insulators," at Pittsburg, March 10, 1904.

By N. J. Neall.

The speaker wishes to call attention to some points in the American practice of to-day.

Iron Poles.—The employment of iron poles for long-distance transmission lines would probably meet with considerable opposition in some cases where the freight and haulage charges are excessive.

A 60 000-volt, 100-mile transmission plant has recently been completed in Mexico, where No. 1 B. & S. gauge hard-drawn, 19-strand copper cables have been supported with porcelain insulators and iron pins by steel cross-arms on steel towers, there being usually 12 towers per mile, normal span 440 feet, although there are some spans of 1300 feet.

The speaker has never heard in American practice that transmission wires take up vibrations in opposite directions, and he believes that the possibility of line wires swinging together would be most remote. A line consisting of three wires in triangular formation swings in unison. On the other hand, it would seem that the construction shown in the paper might cause some difficulty from wires swinging together, and even more annoyance from a wire breaking and falling on a wire below it.

Another condition which appeals to the speaker is the increased vulnerability of the metal transmission-pole to lightning disturbances. It is a well known fact that in the Western United States lightning discharges often shatter wooden poles without impairing the service. Very often, in fact, the operators are not aware that such a circumstance has arisen until the patrolman discovers this fact on his rounds. If we are to follow a highly-insulated metal-line construction, the protective apparatus must be of the highest order to relieve this line of lightning and static discharges. The most common form of lightning arrester abroad is the horn-type, which depends for its operation on the attenuation and consequent breaking of the arc after a discharge over the arrester, which takes considerable time. American practice is represented by a spark-gap or gaps between the line and ground, equipped with resistances in such a way as to cut down the short-circuiting current following a lightning discharge, and so complete the cycle of operation in a very short time. There is at present a tendency in California to try the horn-type arrester on a very large scale, but so far data concerning the worth of this type are wanting and it cannot be considered as strictly representative. Both here and abroad the horn-type arresters for the higher pressures embody some form of series resistance

Insulators.—Both in this paper and the paper by Professor Ryan, we find the crux of the transmission situation to be the insulator. In all other points, generally speaking, high-pressure

operators to-day could, if it became necessary, increase the pressures were it not for the inability of the insulator to stand the increased pressure. It is not clear why the development of the high-pressure insulator has not progressed more rapidly. It may be due to the character of the materials which are considered proper for that device. These are to-day, porcelain, glass, and possibly fibrous material. A common insulator to-day for higher pressure work weighs approximately 12 pounds, and some insulators in successful operation weigh as much as 50 pounds, the latter having stood a long-continued test of 120 000 volts.

It is questionable whether glass insulators can be used for very high pressures, especially if the line should be constructed with metal towers and pins. It is perhaps known that a high-pressure condenser having glass as a dielectric will show a peculiar frosting of the glass surfaces under strain which on close inspection will be shown to arise from a tearing off of glass particles by the static stresses. The same action would doubtless arise in pole-line construction, perhaps in a lesser degree; but inasmuch as the surface of the insulator is a factor in the insulation, this deterioration might have serious results.

[Communicated after Adjournment. Discussing "Automatic Apparatus for Regulating Generator and Feeder Potentials." By A. C. Pratt.]

Several types of pressure regulators, designed to control either the generator field or the exciter field, have as their primary element a solenoid actuated by the potential of the system which it is desired to control; and in some cases further actuated by a current in a separate winding on the same solenoid, from a series transformer in one leg of the main system, designed to compensate for I^2R line losses; but no attempt seems to have been made to compensate also for line drops, due to varying power-factor.

Suppose a fairly long high-pressure transmission system to require 15 amperes charging current. Then 15 amperes at the generating station might represent either no load, or from one-fourth to one-half normal full load at the consumer's end. The common type of regulator, with compensating solenoid as above, might be expected to maintain nearly the same potential at the generating station for the 15 amperes charging as for 15 amperes work-current, but with a wide variation in the potential at the consumer's end of the line. If, however, the current in the potential winding of the solenoid be given a lag relative to that in the current winding, of perhaps 60° or 70° for load at 100% power-factor, then the percentage compensation, due to the series-current winding, will vary with the power-factor. This lag in the potential winding may be produced by tapping from another phase of a three-phase system, or by a combination of inductance and resistance, in series with the potential winding, or both; the

latter expedient allowing ready means of adjustment of the angle of lag by varying the inductance and resistance.

The writer has found that with about the above conditions in the controlling solenoid, the potential at the consumer's end of the line could be maintained nearly, though not quite constant, while the current at the generating station varies from 20° leading to 50° lagging, and from full load to no load.

A paper to be presented at the 177th meeting of the American Institute of Electrical Engineers, New York, May 17-18, 1904.

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NOTES ON FLY-WHEELS.

BY H. H. BARNES, JR.

The choice of a fly-wheel for reciprocating engines direct connected to alternators is a somewhat serious matter in view of synchronous operation. With prime movers giving a uniform torque, and for belted units, a fly-wheel for the general purpose of obtaining a proper mechanical balance for the operation of the engine is all that is required, and the fact that an alternator has to be driven does not enter into the problem. With direct-connected reciprocating engines, however, it is customary to specify a fly-wheel that will limit the angular displacement from the mean position under the worst conditions to a given number of degrees, the limit usually being set at $\pm$ 2.5 electrical degrees. This rule, it has been claimed, gives the best all-round results for the operation of alternating-current machinery. In the following pages an outline has been given of comparative tests of alternators with both light and heavy fly-wheels, the results of which go to show that a good word may also be said for somewhat lighter wheels than the ones to which the above rule leads.

Anyone who has watched the generator instruments in a plant operating alternators in multiple will have noticed a slight periodic swing of the pointers. A closer study of these beats shows there are two distinct varieties. Usually the swing is in step with the revolutions of the engine and is entirely independent of the field excitation of the alternator. In other cases the beats have a distinct period of their own that varies with the field excitation and consequently with the bus-bar pressure. In the first case the variation in the driving torque of the engine, which repeats itself periodically with each revolution, imposes itself upon the alternators and gives forced oscillations. The

variable period, on the other hand, is that of natural oscillation. Natural oscillations invariably appear when an alternator is paralleled a little out of step, and under some other conditions as well, and occasionally even predominate to the exclusion of forced oscillations. At all events, it is an easy matter to determine the natural period experimentally. Its importance and its intimate relation to fly-wheel capacity will be more thoroughly appreciated if we analyze the results obtained in three different plants in which alternators of identical design are direct connected to cross-compound reciprocating engines. The interesting feature in these plants and the reason for singling them out being that, while the generators are identical and the engines nearly so, the fly-wheels differ very considerably in weight.

The generators throughout are 500-kw., two-phase, 100 rev. per min., 60-cycle units of the inductor type. Their short-circuit ratio with no-load excitation is 3.5.

The following table gives the fly-wheel data:

	Fly-Wheel.		Moment of Inertia in lbs. x (ft.)^2		
Plant.	Weight of rim in lb.	Outside diameter in feet.	Fly-wheel.	Revolving element of alternator.	Total.
A	30 000	15	46 150	16 900	63 050
B	50 000	16	92 430	16 900	109 330
C	60 000	18	143 500	16 900	160 400

The natural frequencies obtained experimentally for each plant at no load are shown in Fig. 1 on next page.

It will be noted that the units with the lighter wheels have the higher natural frequency, as was to be expected. The effect of this difference in natural frequency upon the behavior of the engine-governors is marked. With the governor dash-pots in the condition in which the engine builders left them, parallel operation at normal pressure was a failure in all three plants. Upon throwing two units together, cross-currents would build up, and eventually the surging would become so violent that the machines would have to be separated. The frequency of surging was that of natural oscillation throughout. With the same setting of the engine dash-pots, however, the machines in *C* would run together acceptably at no load at pressures of 60% and less of normal, and the machines in *B* at pressures of 40% and

less of normal, whereas those in A failed to operate satisfactorily at 50% of normal, which was the lowest pressure tried.

By artificially decreasing the oscillations of the governors, by means of the dash-pots, the units in A could be made to operate well at normal and higher pressures. The units in B showed an improvement at pressures considerably above normal (tests at reduced pressures had to be omitted here to avoid interfering with the commercial operation of the plant), while no improvement whatever was noticeable in C, except for the lower pressures. The former average limit of 60% of normal being extended to over 80%.

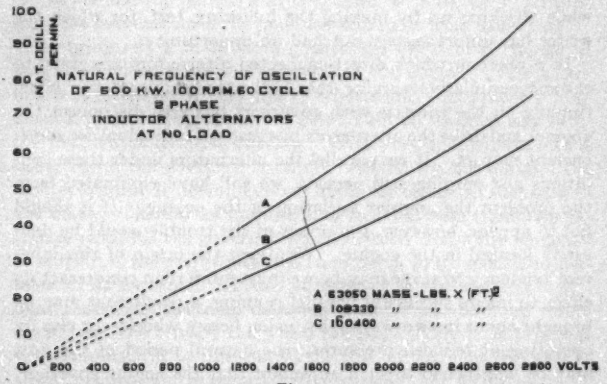

Fig 1.

A still further increase in the damping of the governors in C, however, resulted in a decrease in the limiting pressure, until with completely-blocked governors parallel operation became impossible at any and all pressures. This result and similar ones obtained elsewhere would indicate, it seems, the existence of an inherent tendency toward cumulative surging that is in no way connected with the behavior of the engine governors.

The origin and nature of this tendency are not directly apparent. It seems likely that they are intimately connected with the armature reaction of the alternators, but whether a departure from a uniform turning moment in the prime mover is also essential to its appearance may be doubted. As far as the writer is aware, there is no indication in dynamics in the

theory of forced and natural oscillations of a possibility of forced oscillations producing cumulative surging. If this is so, it might be imagined, although there is no direct experimental evidence to support the idea, that the surging which so frequently appears and is at times so hard to control, in alternators operating in multiple (to limit ourselves to a definite case) is due, not to the lack of uniformity in the turning moment, but rather to the effect of heavy wheels upon armature reaction phenomena. It is also probable that we have operating, in addition to this, causes of the same nature as those that produce cumulative surging in a Watt governor system. It should be clearly understood that this is hardly more than a guess. But it is one that would be worth while checking up by making the following test, for which the writer has unfortunately not had an opportunity.

In a plant in which direct-connected alternators are given to chronic cumulative surging that will not disappear even when running on the throttle with governors blocked, disconnect the engines and drive the alternators by means of individual constant-current motors. If we parallel the alternators under these conditions and surging still persists, we will have eliminated from the problem the angular variation of the engine. If it should fail to appear, however, the origin of the trouble would be definitely located in the engine. Whatever the origin of this inherent tendency to surge may be we must more than counteract its effect to insure successful parallel running, a result that may be brought about in two ways: by using heavy wheels—or else by operating at reduced pressures—the natural period of the unit may be lengthened to such an extent that the engine governor, instead of adding to the disturbance will have time to grapple with any surging that may appear, and wipe it out. An example of this is the behavior of the machines in plants *B* and *C* at reduced pressures. This solution has the drawback of leading to wheels of prohibitive weight for slow-speed units, and furthermore, of making the successful operation of the plant dependent to a certain extent upon the adjustment of the engine governors.

The second and better way to overcome the inherent tendency to surge is to provide sufficient electrical damping. Any oscillations that may appear will then be taken care of by the damping, and the assistance of the governor will no longer be required. In fact the damping action will be more rapid and final if the governor dash-pot is adjusted so that the governor will not respond to natural oscillations, as, in the majority of cases, it

would only strive to maintain the latter if left free to act. As it is easier to adjust the dash-pot with this end in view, to bridge over a short period than a long one, we see that light wheels with their short periods are more desirable in this respect than heavy ones. This argument may seem weak at first when applied to plants in which forced oscillations predominate, but experience teaches that the disturbing influence of the natural period is felt, even when there is no immediate indication of its existence on any of the switchboard instruments. More delicate instruments than the ones usually used would probably reveal the natural period, and even with instruments which appear at first to indicate forced oscillations only, a battle for supremacy between the forced and natural periods may frequently be detected by scrutinizing the movements of the pointers with more than usual care.

To bring out a little more clearly the effect of a change in weight of wheel upon the behavior of the engine governor, we might say that with very heavy wheels and consequently long natural periods the governor is able to kill off unaided any surging that may attempt to develop. With very light wheels, on the other hand, the governor is barely affected by surging and the task of holding it down devolves upon the electrical damping of the units. There is an intermediate zone between these two extremes in which the governor would directly assist the tendency to surge if it were not prevented from doing so by special adjustment of its dash-pot. If such adjustment is not made, it is evident that what electrical damping there is will be more sorely taxed, and the heavier the wheel the more likely it will be that the damping will be unequal to the task of carrying this additional burden and that cumulative surging will set in.

If neither of the conditions we have been discussing is met, as in plants *B* and *C* at normal voltage, successful running may be said to be out of the question. The best remedy for the cumulative surging that will undoubtedly set in in such cases is to increase the electrical damping of the machines, until it is able to hold in check the inherent tendency to surge. This was done in the above plants with eminently satisfactory results.

It may also be pointed out that the successful running at normal pressure with dampened governors in plant *A*, compared with the failure to run in plants *B* and *C*, would indicate that the relative increase in electrical damping is more rapid than the corresponding increase in the inherent tendency to surge for a given decrease in weight of fly-wheel. Should this be corroborated

by similar observations elsewhere, a further most weighty argument would be added in favor of light wheels. However this may be, the tests already described, and they are but a few of those that could be cited, lead to the conclusion that a decrease in fly-wheel capacity is not synonymous with an increased tendency to surge on the part of alternators. The following observations will emphasize this point still further.

In plants *A* and *B* individual exciters are belt driven from the shaft of each alternator, and facilities for paralleling the exciters are provided, besides the usual switches. With this arrangement, if two alternators are paralleled while energized by their own separate exciters, and the pressure and dash-pot conditions are such that cumulative surging sets in, the surging may be very rapidly stopped at all loads by simply paralleling the exciters. Tests were made to ascertain the nature of this action of the exciters. The results proved that it is directly comparable to that of electrical or viscuous damping and not related to the constancy of the exciter pressure.

Other conditions being the same, it is reasonable to assume that the time taken to dampen out cross-currents by paralleling the exciters would give a fair indication of the relative tendency to surge existing in these two plants. Actually, the average time required is about the same in both plants, with possibly a slightly quicker action in *A*. From which the conclusion must again be drawn that a decrease in fly-wheel capacity and consequent increase in angular variation while running does not decrease the stability of the generators. In making these tests it was noticed that individual results in *A* were affected to a very slight extent by the relative position of the driving cranks of the engines. In *B* and *C* and numerous other plants experimented upon, this influence, if it existed at all, was so slight that it was impossible to distinguish it from that due to other causes.

Passing on to another phase of the subject, we find that the limitation usually imposed upon the maximum angular variation of alternators is intended, among other things, to limit the cross-currents due to this variation. Thus, for a variation of $\pm$ 2.5 electrical degrees and a short-circuit ratio of 2.5, the cross-current will amount to approximately 10% of the full-load armature current, and no more. If we consider, however, that a 10% current results in an $I^2 R$ loss of less than 1% of normal, and that the normal $I^2 R$ armature loss is itself but a fraction of the total loss in the generator, we realize that at least a 25% cross-

current may be permitted without fear of appreciably increasing the total losses. Especially as such cross-currents would appear under the most unfavorable conditions of load and cut-off only, the average exchange of current during the day's run undoubtedly remaining well below the maximum. It might be well to add that there should be not any trouble from blinking of the lights if the cross currents do not exceed the value mentioned. There do not appear to be any very good reasons, therefore, why objections should be raised on this score to the use of lighter fly-wheels giving a considerably great variation than the customary 2.5 degrees.

We shall now examine the effect of a light wheel on the generating units upon the behavior of synchronous apparatus. We have in *C* a good example of a plant working under these conditions Exceptionally light wheels are in use there and numerous synchronous motors and rotaries are in operation on the system. Not a trace of trouble has developed in this plant since the start, however, notwithstanding the light wheels.

Some interesting experiments that are very much to the point were made recently by Mr. P. C. Oscanyan. In a plant equipped with 850-kw., 60-cycle, 90 rev. per min. alternators, direct connected to cross-compound reciprocating engines, the fly-wheels were designed to maintain the angular variation within ± 2 degrees of mean. The rims of the wheels were laminated and weighed normally 80 000 lb. With a machine with but one-quarter of its rim in place running singly and in parallel with a completed unit, no difference whatever could be detected between the behavior of the incomplete machine and that of its neighbors. It would operate in parallel under all conditions of load, and when running singly would carry a load of synchronous converters without any indication of trouble. On the strength of this, and without going further, it may be said that surging and allied troubles in synchronous apparatus are not necessarily associated with light wheels and increased angular displacement. They are due, it would appear, more to certain imperfectly understood relations between the number of generating and receiving units, their moments of inertia, output, speed, etc., than to the existence of a more or less pronounced angular variation dependent upon the fly-wheels.

The question of electromechanical resonance remains as being about the only possible further source of trouble that might be introduced by a change in weight of wheel. Resonance, it may

be added by way of explanation, is said to exist in a system when the ratio of forced and natural frequencies is nearly or exactly equal to unity; its effect is a tremendous amplification of the original forced oscillation.

By referring to the curves of natural frequencies on page 345, we see that the normal natural frequency of the units in plant *A* is 81 per minute. The forced frequency determined by the revolutions is 100. By forcing the excitation until we reach pressures and consequently natural frequencies, that are considerably above normal, we might expect to see the effects of approaching resonance. In reality, noticeable cross-currents begin to appear at a frequency of 87; at 90 they are already quite pronounced. They are not cumulative, however (provided the engine dash-pots are in order), but increase and decrease periodically with a main frequency equal to the difference between the forced and natural frequencies. The slip, as it were, between the two frequencies may be counted in this way with great precision. We have here the phenomenon of interference, which appears whenever the damping of a system is very weak. If we increase the damping in this case, as, for instance, by paralleling the exciters, the main period disappears, and the cross-currents take on an average value with a regular but slight beat of forced frequency. A further increase in natural frequency runs up the cross-currents very rapidly until they are far in excess of the full-load armature current for a ratio of frequencies nearly equal to unity. These results show clearly enough that resonance is a real and very serious danger. and one to be avoided with the utmost care, as there is no acceptable way of overcoming it when encountered in practice. In order to avoid it, we should have a formula for predetermining the fly-wheel and the corresponding natural period, which we could then make as different as we choose from the forced period, already determined by the revolutions of the engine.

The oldest and at the same time the best formula for this purpose that the writer knows of, was published by Paul Boucherot in 1892, in Vol. 45, issue No. 31 and 32 of *La Lumiere Electrique*. It is, with a recent slight modification:

$$T = 0.31\, N \sqrt{\frac{M}{f \times E \times I_e \times p}}$$

where

T = Natural period of oscillation in seconds at no load.

N = Revolutions per minute.
M = Total moment of inertia of all rotating parts (fly-wheel, crank discs, inductor or revolving field, etc), expressed in lb. × (ft.)².
f = Electrical frequency per second.
E = Effective e.m.f. per phase or leg.
I_e = Effective short-circuit armature current corresponding to E.
p = Number of phases.

The greatest discrepancy that has thus far appeared in checking this formula experimentally in nearly a dozen plants is one of + 6%, the calculated period being that much longer than the observed one. The mean error for all the plants was + 3%. The reliability of the formula for practical purposes is therefore beyond doubt.

With this formula to assist us, it is an easy matter to predetermine a fly-wheel that will at least avoid resonance once we have agreed upon the closest ratio permissible between the forced and natural frequencies. The choice of this ratio depends upon numerous considerations. In the first place we have, as the essence of resonance, the increase in angular variation that is bound to appear after paralleling, even when absolute resonance is still quite remote. There is also the possible error between the calculated and the actual fly-wheel, the rather doubtful values that are sometimes used for the short-circuit current and the increase in natural frequency with the load and with a decreasing power-factor. Making due allowance for these various factors, let us assume for the moment a natural frequency at no load equal to 70% of the forced.

If we introduce this condition into the formula on the preceding page, and substitute $P \times k$ for $E \times I_e \times p$, and $W r^2$ for M wherein P is the normal output of the alternator in kilowatts, k, the ratio between the short circuit and full-load armature current, W the weight in lb. and r the radius of gyration in feet of all the revolving parts combined, we get

$$W r^2 = 25 \frac{P \times f \times k}{\left(\frac{N}{100}\right)^4}$$

It remains to be seen if a wheel based on this formula is sufficiently heavy to keep the cross-currents within bounds. It appears upon examination that for such a wheel the maximum cross-current between alternators driven by any average cross-

compound steam-engine would not exceed 25% of the full-load armature current, even under the worst conditions, which may be considered an entirely permissible figure.

For an ordinary cross-compound unit and a short-circuit ratio of $k = 2.5$, the maximum angular variation may be assumed to be within $\pm$ three electrical degrees of mean when running singly. With a 70% ratio of frequencies, however, the angular variation of a unit running singly will be practically doubled upon paralleling it in with its fellows, and it is upon this increased variation that the calculation of the cross-currents has been based. With alternators with a higher short-circuit ratio and therefore better regulation, the angular variation will be less on account of the heavier fly-wheel called for by the formula. The cross-currents, on the other hand, remain the same for a given type of engine regardless of the regulation of the alternators. With single-crank engines these currents will be somewhat heavier than with cross-compound engines, and with multi-cylinder engines a trifle less. The difference in the latter case will hardly be sufficient to demand a separate formula, and the same may be said of vertical as compared with horizontal types of engines. With single-crank engines, however, the maximum angular variation should be determined and if the design of the engine is such that the variation in a single engine materially exceeds $\pm$ three electrical degrees, it would be advisable to modify the constant in the formula to a slight extent.

While there are apparently no disadvantages connected with the use of relatively light wheels, there are, at least, two distinct advantages that should not be overlooked. We have already seen that a light wheel means a high natural frequency for which it is relatively easy to get the engine governors to behave properly. In practice this is a very real and important advantage, and one not to be lightly dismissed.

A considerable saving in first cost may also be affected by using lighter wheels, especially in the case of slow-speed units, where the amount of iron that may be saved in the fly-wheel foots up to quite a respectable sum. At the same time the general wear and tear upon the bearings of the engines are lessened.

We believe, therefore, that the formula given above may be used with perfect safety in predetermining fly-wheels for direct-connected steam-engine drive, with the following exceptions. For high speeds the wheels obtained, while meeting all electrical requirements, would hardly be heavy enough to give the engine a proper mechanical balance, and in such cases

heavier wheels, as determined by the engine builders, should be used. Variations of the formula will also suggest themselves in individual cases. Thus, for instance, with engines giving an exceptionally even driving torque connected to alternators of excellent regulation, the permissible ratio between natural and forced frequencies might be advanced to 0.75 or even more without serious risk of encountering resonance phenomena or of introducing troubles of other origin. With single-crank engines, on the contrary, it will occasionally be necessary to use a somewhat heavier wheel than the one indicated by the formula.

To sum up our main conclusions, we may say that the fly-wheel—as distinct from the assistance given either by the engine governor or the damping of the unit—is impotent to ensure satisfactory synchronous operation. Except for these two influences, the inherent tendency toward cumulative surging existing in the unit would predominate, and parallel running would be impossible.

It also seems advisable to use a somewhat lighter fly-wheel than would be considered conservative practice to-day. This greatly facilitates the adjustment of the engine governors while it does not decrease the stability of the system. For it would appear that the electrical damping of the units (which varies with their natural period and consequently with the fly-wheel) at least retains its relative strength as compared with the inherent tendency to surge for wide variations in weight of wheel. Therefore, if the damping is sufficient to hold the tendency to surge in check when a heavy wheel is used, it remains so for a light wheel. This argument applies to a change in weight of wheel for a given generating unit only, and should not be construed as one in favor of increased angular variation as such.

We also find that electromechanical resonance is a serious danger that must be avoided by making a proper choice of fly-wheel. A wheel selected with this end in view is at the same time satisfactory for general operating purposes, provided there is sufficient damping in the unit to check the inherent tendency to surge.

If we inquire, in concluding, what fly-wheel capacity suggests itself for direct connection to gas-engines, it must be said that it would be a little venturesome to advance a cut and dried rule at present in view of the limited practical experience with this type of prime mover. By analogy with steam-engine experience, however, it may be said that light fly-wheels and vigorous electrical damping is the combination that is most likely to win out for this class of work.

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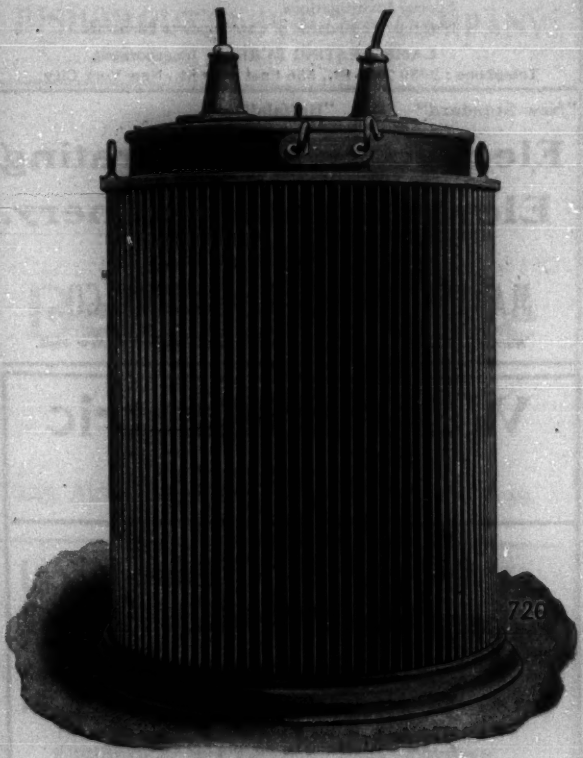

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